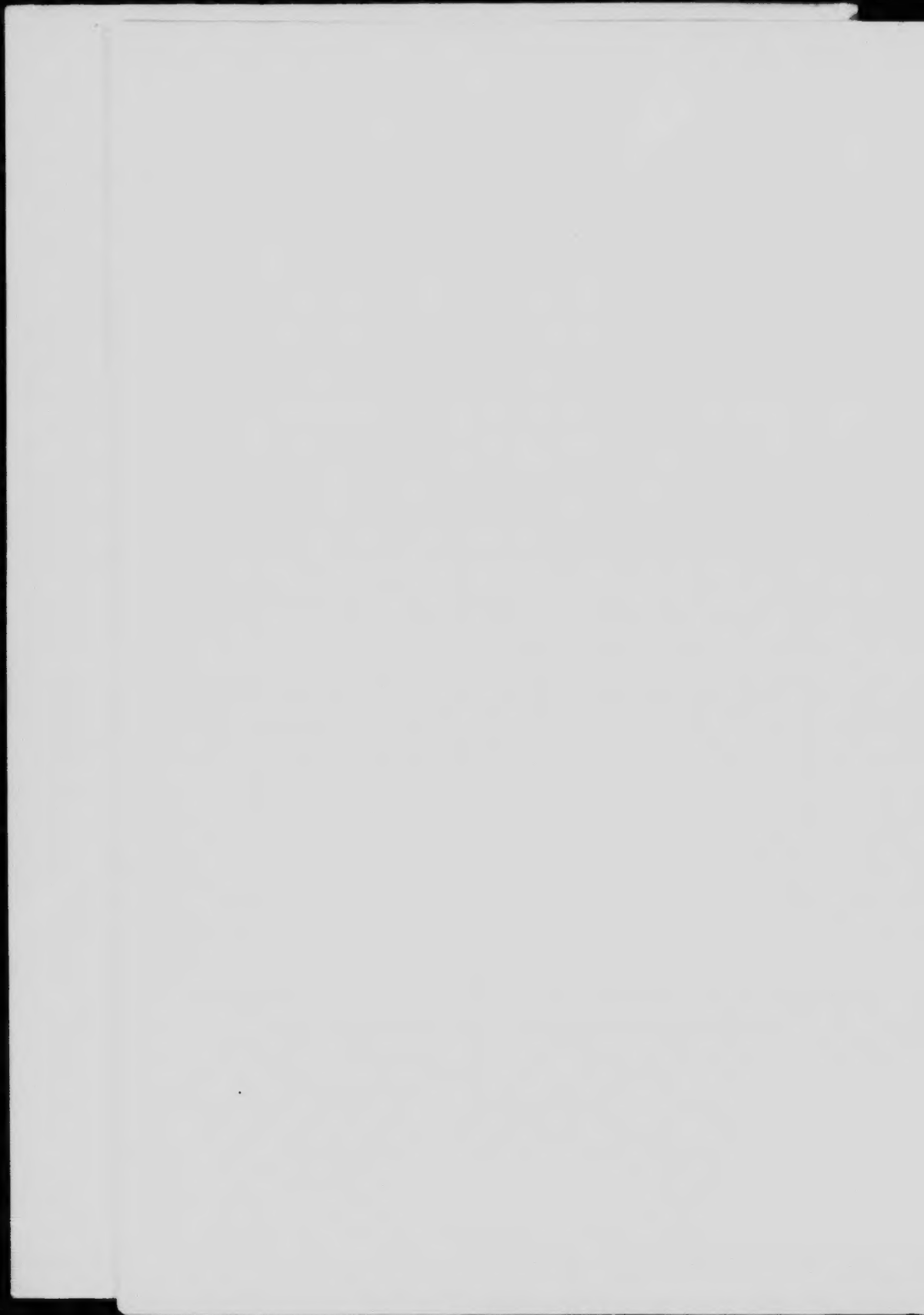




**ELECTRICITY IN THE SERVICE
OF MAN**

ELECTRICITY

IN THE

SERVICE OF MAN

**A POPULAR AND PRACTICAL TREATISE
ON THE APPLICATIONS OF ELECTRICITY
TO MODERN LIFE**

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Heriot-Watt College, Edinburgh**

WITH OVER 1,600 ILLUSTRATIONS

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ELECTRICITY

IN THE SERVICE OF MAN

PART II

The Technology of Electricity

INTRODUCTION

IN the pages of Volume I. we have endeavoured to place before the reader the main experimental facts of electrical science and the principles which appear to underlie those facts as interpreted by the foremost scientific men of the nineteenth century. Incidentally, and as having an abiding interest to all who approach this fascinating subject, we have briefly sketched the history of the development of the various converging lines of scientific advance by which the present position of the science has been reached, and have described the earlier attempts to adapt the growing science to the service of man in various directions.

The pages which follow will be devoted to what, in a general sense, may be called the technology of electricity—that is, to an account of the details of the methods by which the principles already described have been, and are being, applied in multifarious directions to the needs and necessities of mankind. So intimate, however, are the action and reaction of theory and practice upon one another in this complicated subject, that it is absolutely impossible to separate and place in water-tight compartments the purely scientific and the strictly technical sections. Most of the chief scientific principles and laws have been referred to in the pages of Volume I., but from time to time we shall have to refer to others more recently discovered, or so intimately bound up with special applications that it is not possible to deal with them adequately without full reference to these applications. On the other hand, we shall endeavour to avoid repetitions of the theoretical scientific conclusions already fully set forth, and with which we shall assume, from this point onward, that the reader is familiar.

On a review of the field of work to be dealt with, it appears to fall naturally into two great divisions. In one of these large quantities of energy are handled, and considerations of economy of transformation and utilisation dominate every part of the subject. It includes the generation and transmission of electrical power in bulk, and all applications of such power to electric lighting, electric traction, electric motors, and electro-chemistry. In the other division, the amount of energy involved is inconsiderable, and the cost of obtaining it is either actually or relatively of little consequence: other considerations, such as convenience, reliability, costs of installation and upkeep, etc., are the factors which determine the course of the development. Under this division fall the very important subjects of Telegraphy and Telephony, as well as several minor, but still important, applications to signalling, intercommunication, etc.

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DIVISION I

The Generation, Transmission, and Utilisation of Electrical Power

CHAPTER I

CONTINUOUS CURRENT GENERATORS

THE main object of the design in all electric generators depending on Faraday's laws of magneto-electric induction is to arrange electric conductors and magnetic fields in such relative positions that the necessary electro-motive forces and the consequent currents may be produced by their relative motion under the most economical conditions, both as regards the capital expenditure involved in the first cost of the machines and the subsequent efficiency of working and cost of upkeep of the plant. In the previous volume (pages 470 to 565) we have described the general methods of application of the principles involved to the construction of actual machines in the earlier and later stages of their development. Some space has also been devoted to the consideration in an elementary manner of the theory underlying these methods. We have now to refer to subsequent developments as exemplified in modern machines, and to deal with various technical details which have been left over from the previous section, as they would there have tended to obscure the more fundamental scientific principles that were being considered. We shall, as before, deal with continuous current machines first, and in their treatment follow the same order as in Chapter XIII., Volume I., as far as may be convenient.

The most conspicuous trend of the developments of recent years has been the tendency to concentrate the generation of electrical power in large stations placed either near the source (waterfall, coalfield, etc.) from which the energy is to be obtained, or in some position, relative to the area of consumption, in which the cost of generation and transmission can be reduced to a minimum. Both in these islands and abroad great numbers of so-called central stations have been erected and equipped, and the necessity for the would-be consumer to generate the current he requires has been correspondingly diminished. As regards the machines, therefore, the period named has witnessed the production of units which have become larger and larger year by year, and in the design of which fresh problems

have continually been presented for solution. Though there is still a field for the use of small generators, their production has certainly diminished relatively and, perhaps, even absolutely, but it is difficult to obtain statistics which, to be accurate, would have to be world-wide.

I.—CLASSIFICATION

For convenience of treatment it would seem desirable at the outset to classify, if possible, the various types of machines which merit attention. A very cursory examination, however, shows that a simple and exhaustive classification is not possible, and that the classification which is most convenient from one point of view is not the best from another, the various systems available cutting across one another in all directions.

Speed.—For instance, from the engine builder's point of view the question of speed, combined perhaps with steadiness of running as affected by a large moment of inertia in the revolving parts, is of paramount importance. In the early days of the construction of dynamos the most ordinary speeds varied from about 750 to 1,200 revolutions per minute. As no steam engine was then commonly produced which ran anywhere near these speeds, rope or belt driving had to be employed. The advantages of direct coupling of dynamo and engine were, however, obvious, and led the dynamo builders on the one hand to produce dynamos speeded for lower and lower speeds, whilst the engine builders designed engines running at higher speeds than were once thought possible or economical. Thus at a comparatively early date combined sets consisting of a high-speed engine directly coupled to a slow-speed dynamo became fairly common.

The development has, however, proceeded far beyond the meeting point of the two speeds, for to-day slow-speed dynamos are built which can be directly coupled to engines running at less than 100 revolutions per minute, whilst in the modern steam turbines we have engines whose speed is greater than that of any ordinary dynamo, and for coupling to which special high-speed dynamos have to be designed. Indeed, in some cases step-down gearing has to be introduced between the engine and the dynamo, the speed of the former—in some cases 7,000 revolutions per minute—being far too high for convenient handling in the design of the dynamo. Even with reciprocating engines and modern dynamos the overlap of speed is considerable, so that the user can now choose good combinations of engines and dynamos either direct-coupled or not, according to the requirements of the particular case in hand.

Although, therefore, the question of speed has not now the paramount importance that it once threatened to have, or rather because it is important for somewhat different reasons, it is convenient to divide dynamos into slow, medium, and high-speed machines. Machines of practically any speed down to or less than 100 revolutions per minute can be built

but as a rule the slower the speed the more costly is the machine for a given output. On the other hand, the excessively high speeds of turbo-dynamos have so profoundly modified the details of their design as to make them practically a class by themselves.

Magnetic Circuit.—Another method of classification may be found in the general design of the magnetic circuit. Several typical designs have already been described (see pages 497 to 500, Vol. I.), but many of these have now become obsolete, and serve only as a basis of classification for historical machines. In the last edition the number of poles was made a basis of classification, and it was found convenient to divide the bipolar machines into several sub-classes. This is no longer necessary, for the number of bipolar generators now built is not very large. Generally speaking, it may be said that for slow speeds multipolar field magnets are used in modern machines, whilst for medium and high speeds the simpler two-pole or at most four-pole machines are selected. As between the various classes of bipolar machines, it may be remarked that the single magnetic circuit is the better design magnetically, but that the double magnetic circuit usually leads to a machine mechanically better and steadier.

Armature Cores.—Though not so striking as the general arrangement of the iron of the field magnets and the armature, the shape given to the thin armature stampings to allow for the winding of the copper conductors is important, and may be taken as a subsidiary basis of classification connected with the magnetic circuit. These stampings as already explained, are built up to form the iron core of the armature, which when finished will fall into one of the following classes:—

- (a) Smooth-core armature.
- (b) Slotted armature.
- (c) Tunnelled armature or armature with buried conductors.

The slotted armature, especially when supplied with "semi-sunk" conductors, lies intermediate between the other two, and according to the shape of the slots approaches the smooth core or the "tunnelled" core in its properties. This is a "cross" classification, as any one of the cores described may be used with any of the field magnets referred to previously.

Excitation.—From the point of view of the purpose for which the machine is to be used and of its regulation, automatic or otherwise, whilst running, the method of excitation of the field magnets may be used as another basis of classification.

It has already been pointed out (see page 506, Vol. I.) that the field magnets may be excited by the whole current of the machine (*series* excitation, Fig. 483), or that they may be excited by the current in a shunt circuit placed directly across the brushes or terminals of the machine (*shunt* excitation, Fig. 484). There is, however, a third method of excitation known as *compound winding*, which is a combination of the other two.

In this method there are two exciting circuits; one, consisting of thick wire coils and called the *series* circuit, carries either the whole *external* current, as in Fig. 1, whilst the fine wire or *shunt* circuit is directly joined to the two *brushes*. Or, in another method of connection, depicted in Fig. 2, the *series* circuit carries the whole *armature* current and the *shunt* circuit is joined to the *terminals* of the machine. The first of these methods of connection is known as "Series and Short Shunt," and the second as "Series and Long Shunt."

The object of using two magnetising coils on the field magnet is to regulate automatically the voltage or P. D. at the terminals so that this

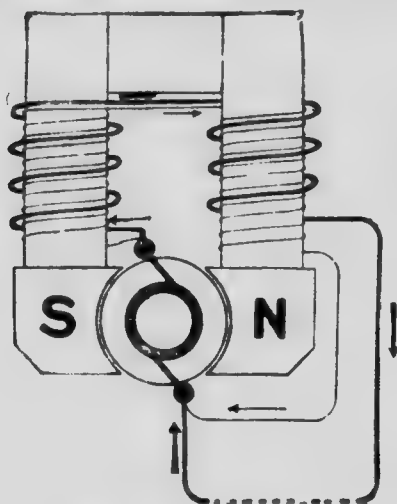


Fig. 1.—Series and Short-Shunt Compound Winding.

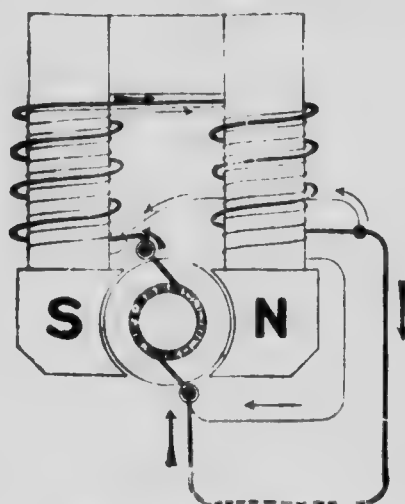


Fig. 2.—Series and Long-Shunt Compound Winding.

voltage shall remain constant at all loads. The details will be referred to later under the head of "regulation" (see page 177). For some purposes machines are *over-compounded*—that is, the exciting coils are so arranged that the voltage at the terminals rises with increase of load.

Occasionally it is found convenient to use an entirely separate source for the excitation current for the field magnets, and in such cases the machine is said to be *separately excited*.

The various purposes for which these different methods of exciting the field magnets are generally employed may be summarised as follows:—

(i.) *Shunt winding.*

- (a) Central station glow lamp working.
- (b) Secondary battery charging.
- (c) Electro-chemical work.

- (ii.) *Series winding.*
 - (a) Series arc lighting.
 - (b) Long-distance transmission
- (iii.) *Compound winding.*
 - (a) Isolated plants in public and private buildings.
 - (b) Central station work generally.
 - (c) Traction generators.
- (iv.) *Over-compounding.*
 - (a) Traction generators.
- (v.) *Separate excitation.*
 - (a) Low voltage, large current machines for certain electro-chemical work.
 - (b) High voltage, constant current machines for long distance transmission.

Armature Winding.—Dynamos are sometimes classified according to the method adopted for the winding of the armature. The greatest differences from this point of view are those existing between *open-coil* and *closed-coil* windings. The latter may be subdivided into *ring*, *drum* and *disc* windings, the two former being by far the most widely used. Further subdivisions could be made, and the relative merits of the various systems will be discussed later. The leading methods have been already described in Volume I. (pages 486 to 497). As a basis for classifying the machines, however, this particular detail of design does not serve any very useful purpose in dealing with modern machines.

Voltage.—Whilst, generally speaking, the size of a machine depends upon the maximum output and rated speed for which it is designed, the question of the voltage or pressure at which the energy is to be delivered may profoundly modify the design, and hence may be adopted as another subsidiary basis of classification. Thus a 500-kilowatt machine designed to give a pressure of only 50 volts must deal with 10,000 amperes on its commutator, whilst a machine with the same output at 1,000 volts has only to handle some 500 amperes. In one case the commutation of the heavy current is the chief difficulty, whilst in the other the insulation for the high voltage and the prevention of flashing over, and other similar troubles, have to be provided for.

II.—THE MAGNETIC CIRCUIT; THE FIELD MAGNETS

It will be understood from the laws of the magnetic circuit (*see* page 282, Vol. I.) and the general principles of the construction of electro-magnets (*see* page 330), especially of dynamo electro-magnets (*see* page 497), that the magnetic circuit of a continuous current dynamo must be treated, in the final resort, as a whole, and that the magneto-motive force required to produce a required flux in the active part of the machine depends

upon the design and dimensions of all parts of the circuit. Nevertheless, it will be convenient in the first instance to take the different parts of the circuit separately, and to examine how they have been dealt with and modified in actual machines. For this purpose it is intended to postpone the consideration of the armature core, and to consider first the field magnet part of the circuit.

Bipolar Machines, Single Circuit.—As already explained, this type of machine does not bulk largely in the total production of modern generators, except in the special case of turbo-dynamos, which will be dealt with separately: it is therefore only necessary to refer briefly to some of the developments which followed the historical machines described in Volume I.,

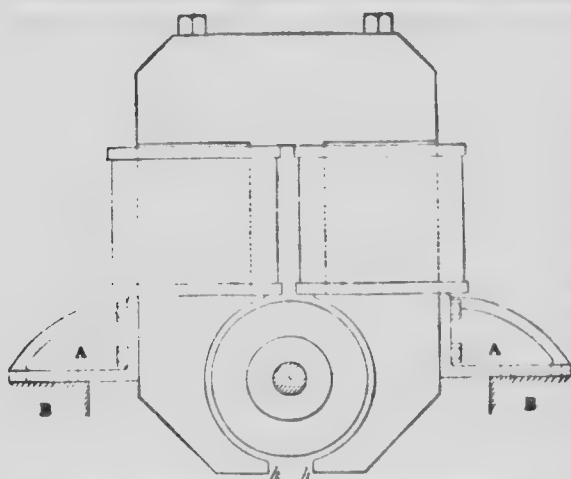


Fig. 3.—Magnetic Circuit of an Undertype Machine.

but which in their turn have nearly dropped out of use. In the single-circuit bipolar machines we have the simplest and most easily constructed types of a dynamo magnetic circuit. The chief magnetic requirements, as already pointed out, are short thick cores for the magnetising coils, heavy yokes, and an ample quantity of iron in the pole pieces.

(a) *Undertype.*—Attention has already been directed (see page 526,

Vol. I.) to one of the chief magnetic defects of this type of magnet circuit, namely—the magnetic leakage through the iron of the bed-plate which is magnetically in parallel with the iron of the armature core. The difficulty was met in some cases by interposing a thick non-magnetic footstep, usually made of zinc and about five inches deep (Figs. 498, 500, and 501, Vol. I.), between the iron of the pole pieces and the iron of the bed-plate. This device rendered the leakage less copious by increasing the reluctance of the leakage path, the portion of which passing through the bed-plate must include a length of, at least, ten inches in non-magnetic material.

Another method of reducing to a minimum the magnetic leakage through the bed-plate was to support the magnets by solid gun-metal brackets at the side, these latter being bolted to the outer frame of the bed-plate, the iron of which is cut away beneath the poles of the machine as in Fig. 3, which shows diagrammatically a field magnet and armature, with the supporting

brackets *AA* bolted to the bed-plate *BB*. The iron bed-plate is thus removed to a distance from the gap *hh* between the horns of the pole-pieces.

(b) *Overtyp*e.—The arrangement of the magnetic circuit in this type has been shown diagrammatically in Fig. 475 (*b*), Vol. I., and an example of actual machines was given in Fig. 502. The type was a favourite one with English and Continental makers in the early years of this century for machines with an output up to about 80 kilowatts, and it was used with both ring and drum-wound armatures. A good modern example has also been shown in the coupled transformer plant of Messrs. Johnson and Phillips (Fig. 608, Vol. I.) with reference to which we give in Fig. 4 a diagram of the magnetic circuit at right angles to the axis of rotation.

One great advantage of this type of field magnet is that the iron of the bed-plate quite conveniently forms the yoke part of the magnetic circuit, and thus serves a double purpose. This will be evident from an inspection of the figures referred to above. Other methods of securing this object were described in the last edition. The chief mechanical disadvantage is that the axis of rotation is relatively high, necessitating high pedestals for the bearings.

(c) *Iron-clad Type*.—This type of single magnetic circuit has been shown diagrammatically in Figs. 477 and 506, Vol. I. There are often two magnetising coils

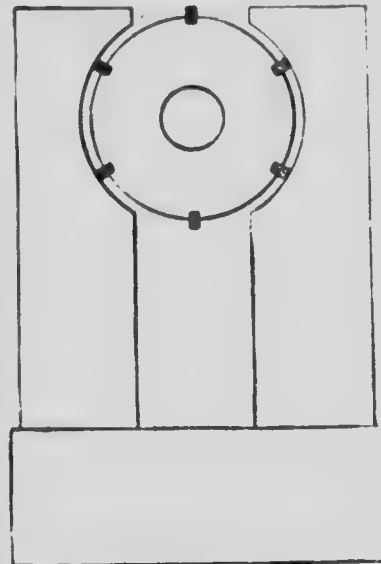


Fig 4.—Magnetic Circuit of an Overtyp Dynamo.

magnetically in series, as in the undertyp and overtyp machines; but these coils are placed either directly on the poles or very close to them. It might be argued that the circuit shown in Fig. 506 is a double and not a single magnetic circuit; the lines flowing horizontally across the armature may complete their circuit by passing back through the iron by any of the enclosing paths. A closer examination will, however, show that the whole of the useful lines pass through both magnetising coils, whose *M. M. F.*'s are therefore in series, and that it is the yoke iron only which is split and offers alternative paths to the returning lines. The term "double magnetic circuit" is, however, better restricted to those cases in which there are two, or two groups of, magnetising coils placed magnetically in parallel, the lines set up by one coil or group not passing through the other, but completing an independent circuit. Similarly, the magnetic circuit of

Fig. 477, Vol. I., is a single magnetic circuit only, since there is but one magnetising coil and all the lines generated pass through it, though there are alternative return paths.

Full details of the machine referred to in Fig. 477 and also of the curious and interesting Thomson-Houston arc-light dynamos were given in the technological section of the last edition of this book and will repay perusal by those interested in the historical development of dynamos.

Bipolar Machines, Double Circuit.—(a) *Open Type*.—The machines of this type were numerous, and exhibited considerable variety in the details of their design. Some of the forms are given diagrammatically in Vol. I. (see Fig. 475 (d), (e), and (f), and Fig. 495), whilst actual machines were described and illustrated in Figs. 492, 493, 494, and 496. They have played an important part in the development of generators for electric lighting purposes, and are still widely used for isolated plants. The more modern forms, however, do not show any marked difference in their magnetic circuits from those already described, and therefore we do not propose to illustrate them further.

(b) *Iron-clad Type*.—In bipolar machines with double magnetic circuits the iron-clad type of machine, which was never very widely used, has become quite obsolete as a generator. Where it still persists it is chiefly used for motor purposes, and therefore we may pass it over here without further comment, leaving such remarks as may seem desirable to a subsequent chapter on Motors.

Four-Pole Machines.—(a) *Open*.—Though, strictly speaking, these may be regarded as multipolar machines, they form a sufficiently large class to be dealt with separately, especially as sometimes the design of the magnetic circuit is modified in a way that is either not possible or not convenient when the poles are more numerous. The most usual disposition of the various magnetic circuits is shown diagrammatically in Fig. 510, Vol. I., but another form magnetically very different (Figs. 508 and 509) has also been described and illustrated.

The polygonal form of yoke with magnet cores projecting inwardly from the flat sides, as shown in Fig. 510, has been to a great extent replaced, even in four-pole machines, by the cylindric form. Where the number of poles is greater than four the cylindric yoke is almost universally adopted. It has the advantage of giving a neater appearance to the machine, and as it presents fewer sharp edges there is less tendency for magnetic leakage. A four-pole machine of this form is illustrated in Fig. 5, which represents a 60-kilowatt machine constructed by Messrs. Johnson and Phillips a few years ago. The lower part of the yoke dips into a pit in the bed-plate, by which it is supported on substantial brackets which are part of the yoke casting, which, in this instance, is in halves, divided along a horizontal

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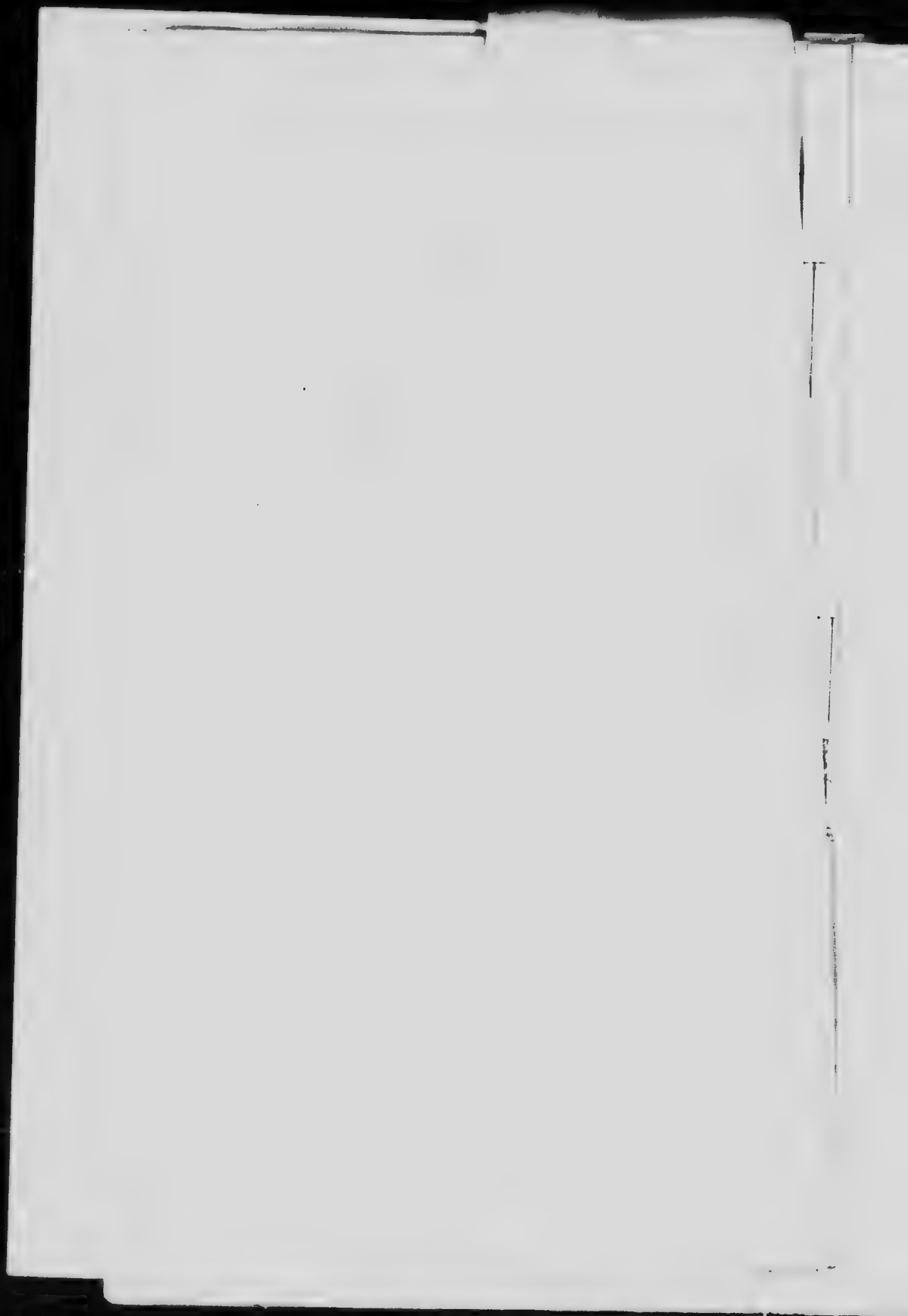
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(Open type with Outboard, running and load)



diameter. This method of construction reduces the height of the shaft and of the pedestals which carry the bearings, and is therefore in accordance with sound principles of mechanical design. The bolts by which the magnet cores are attached to the yoke can be seen in the figure. Full details of this and other methods of attaching the cores to these circular yokes will be given later.

In Plate I. is given a scale drawing, consisting of an end and a side



Fig. 5.—60-Kilowatt Four-pole Dynamo.

view, each partly in section to show details, of a standard four-pole eight-kilowatt machine constructed by Messrs. Bruce Peebles and Co., of Edinburgh. In this case it will be noticed that the whole of the magnet ring is above the horizontal plane of the bed-plate to which the brackets carrying the ring are bolted (Fig. 6), and that therefore the single pedestal which is shown in the plate is relatively longer than the pedestals in Fig. 5. This is permissible, however, because this machine has an output of eight kilowatts

only, whereas the machine shown in Fig. 5 is a 60-kilowatt machine. A reference to the dimensions given on the plate shows that the pedestals though relatively long, are only 15 inches high to the centre line of the shaft.

The general external appearance of the machine is shown in Fig. 6, which differs from Plate I., inasmuch as the machine is shown with three bearings and a wide driving pulley, whereas in the plate only one bearing

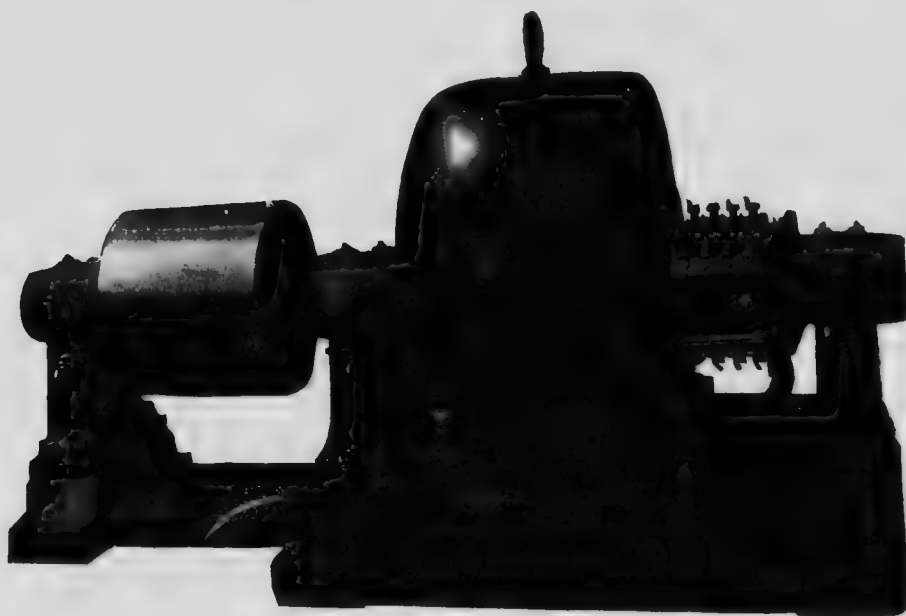


Fig. 6.—Eight-Kilowatt Four-pole Dynamo.

is shown, there being a half-coupling at the other end of the shaft for direct connection to the shaft of a steam engine or other prime mover.

The principal dimensions of the machine and of its more important details are given on the plate, in which the upper halves of the two figures are shown in section. These details will be fully referred to later, and therefore attention need only be called here to the neat and compact appearance of the machine, and to the exceptionally deep flanges on the yoke ring, which, with the polar projections, is cast in halves, divided along a horizontal diameter. These deep flanges, besides improving the appearance of the machine, tend to protect the magnet windings from mechanical injury.

(b) *Iron-clad*.—As in the bipolar machines, the four-pole machines of the iron-clad type are now chiefly used for enclosed motors, and we shall

therefore defer their consideration to the chapter on continuous current motors.

(c) *High-speed Turbo-Dynamos.*—As already explained, the high speeds at which dynamos can be driven by steam turbines make it possible to obtain the usual voltages with a comparatively small number of poles, and at the present time turbo-dynamos, as they are usually called, are most frequently built with four poles, and therefore fall naturally into the present section.

The high speed of the armature or rotor introduces new problems peculiar to itself which will be dealt with subsequently, but these problems, and especially those connected with commutation, react on the design of the field magnet, and in most types of turbo-dynamos have led to striking developments. Put briefly, it may be said that whilst the general method is to employ an encircling yoke ring with the magnetic flux directed inwards from it, as in the lower speed machines, this flux is sometimes carried by salient cores projecting inwards in the usual way, whilst in other cases the pro-

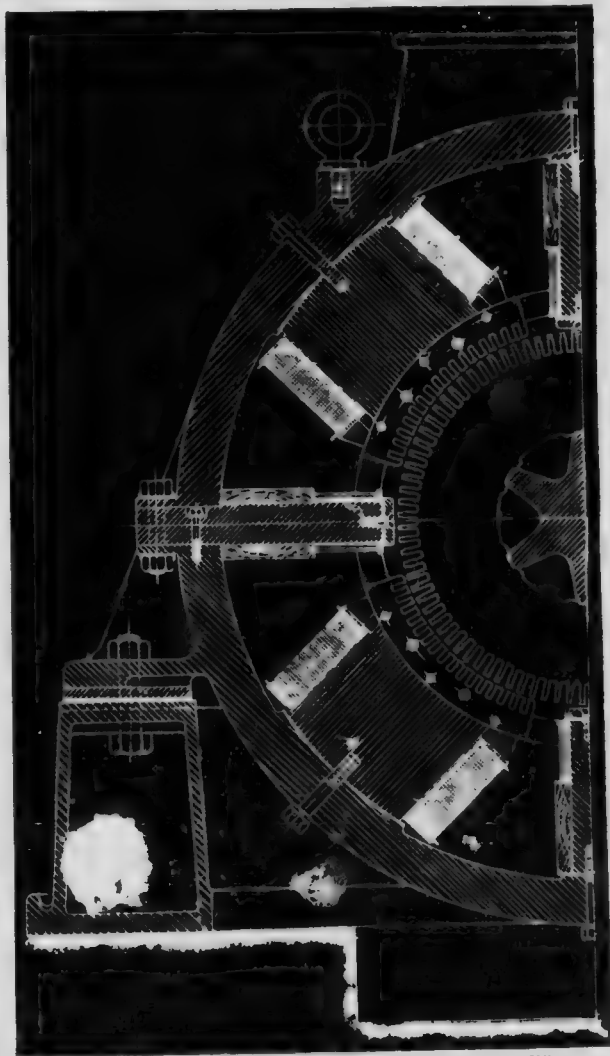


Fig. 7.—Cross-Section of the Magnetic Circuit of a Brush 750-Kilowatt Turbo-Dynamo. (Speed of Rotor, 2,400 R. P. M.)

jecting iron more nearly resembles in its general arrangement the iron of the stator of an induction motor.

These two general plans will be readily contrasted by an examination of Figs. 7 and 8. The first is a half-section perpendicular to the axis of the magnetic circuit of a four-pole turbo-dynamo built by the Brush Electrical Engineering Company, and designed for an output of 750 kilowatts at 480 to 520 volts at a speed of 2,400 R. P. M. The internal diameter inside the pole faces is 24 inches, from which the general dimensions of the machine can be inferred.

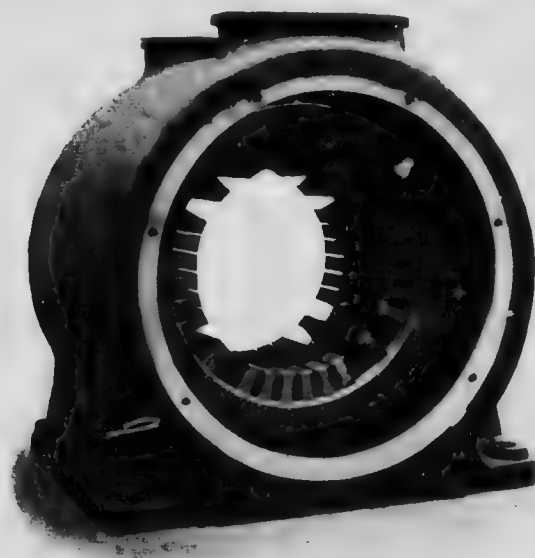


Fig. 8.—Turbo-Dynamo; Unbound Field-frame and Core.
135 Kilowatts (Speed of Rotor, 2,700 R. P. M.)

It will be noticed that the cores of the magnets are bolted to the yoke frame in the same way as is often adopted in slow-speed machines and that the magnetising or exciting coils are in the usual position. The difference lies in the pole pieces or pole shoes, which have an exceptionally long radial depth, and are slotted on the face turned towards the armature; they are also laminated. The reasons for, and use of, these slots, as well as of the interpolar projections, will be explained later.

One of the chief criticisms of the adoption of this general form of design of the field magnets, which has been found so admirable for slow-speed machines, is that at the high speeds used the losses by windage are excessive, since to the smooth surface of the armature, discharging air through its numerous ventilating ducts, is opposed the intermittent surface of the salient pole faces between which are comparatively large spaces, in which all kinds of air eddies, leading to loss of energy, can be set up.

The other type of magnet frame is shown in Fig. 8, which represents the field carcass without the windings of a 135-kilowatt turbo-dynamo built by Messrs. Brown, Boveri and Co., of Baden. Core plates, slotted as shown, are carried by a rigid frame, the plates being so arranged as to allow air-passages of ample size to ensure the efficient ventilation of the windings.

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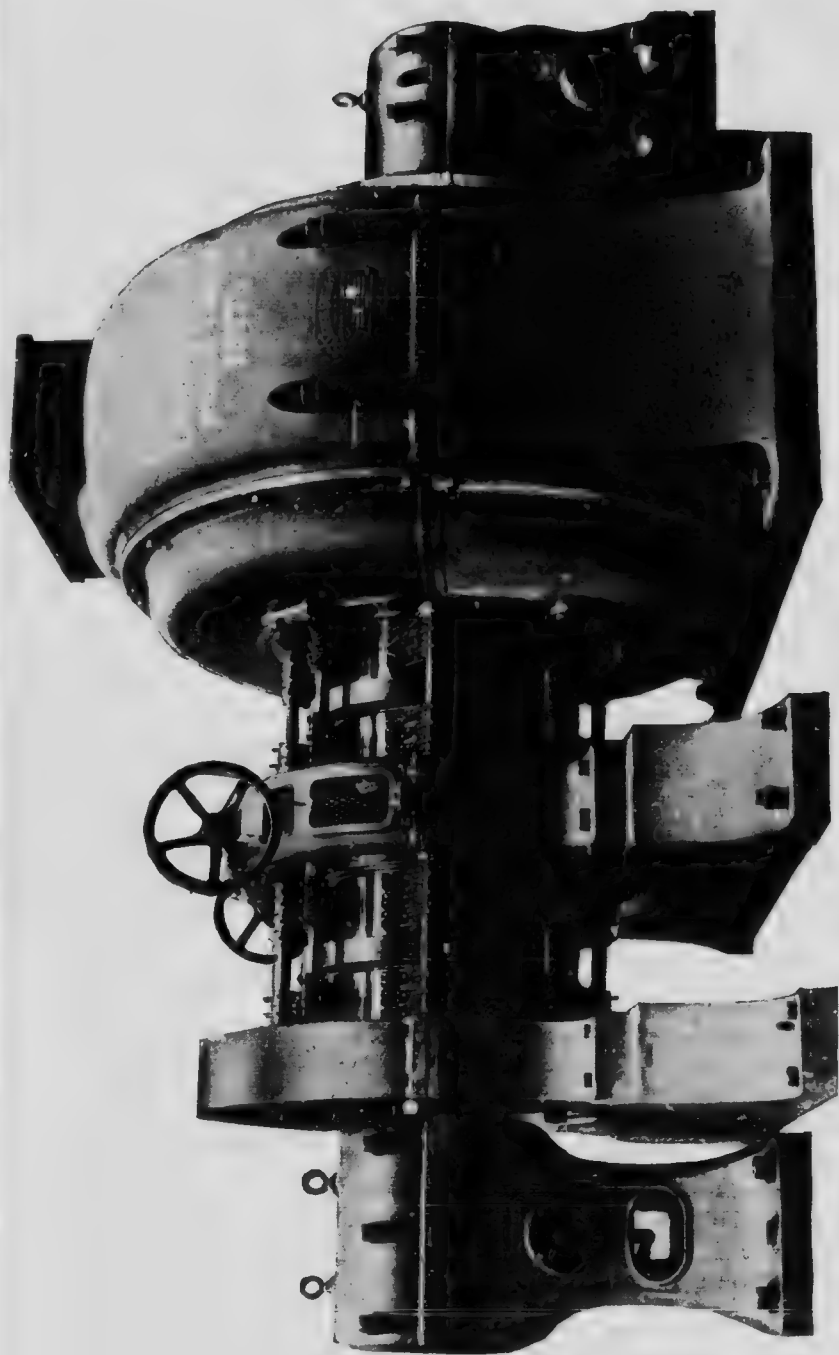


Fig. 9.—Siemens Turbo-Dynamo, 1,200 Kilowatts at 1,800 R. P. M.

In this case the outer frame acts as a housing, as in an induction motor, and is not intended to be an effective part of the magnetic circuit. This will be more clearly seen from an inspection of the right-hand figure on Plate IV., which represents an end view, partly in section, of a similar Brown, Boveri machine designed to give 500 kilowatts and 250 volts at a speed of 2,100 R. P. M. As in the Brush machine, the pole faces are slotted. The method of winding will be discussed later.

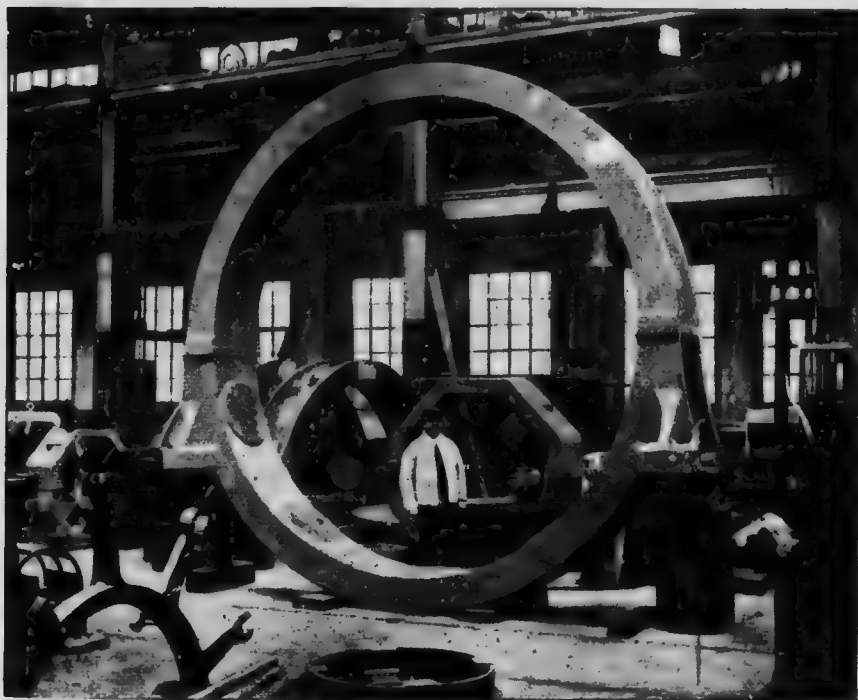


Fig. 10.—Yoke Ring, Early Pattern of Ten-Pole Mather and Platt Dynamo.

The appearance of a large machine of this type is well shown in Fig. 9, which represents a turbo-dynamo built by Messrs. Siemens Bros.' Dynamo Works, Ltd., for Devonport. This machine gives 1,200 kilowatts at 460 to 500 volts, when running at 1,250 R. P. M. It is an eight-pole machine, stands 9 feet high above the engine-room floor, and covers a floor space of 14 feet long to face of coupling by 7 feet 6 inches wide. Further details, more especially as regards the commutator, will be given subsequently (see page 139).

Multipolar Machines.—(a) *Slow Speed.*—For continuous-current dynamos of moderate and large output this form of field-magnet design is

now universally adopted wherever the machine has to be driven by a reciprocating engine, for which purpose the design assumed great importance of recent years in consequence of the erection of large generating stations for traction as well as for lighting purposes. Large rotary converters are also built with multipolar fields, and the use of such field magnets has only recently been checked by the development of turbo-dynamos.

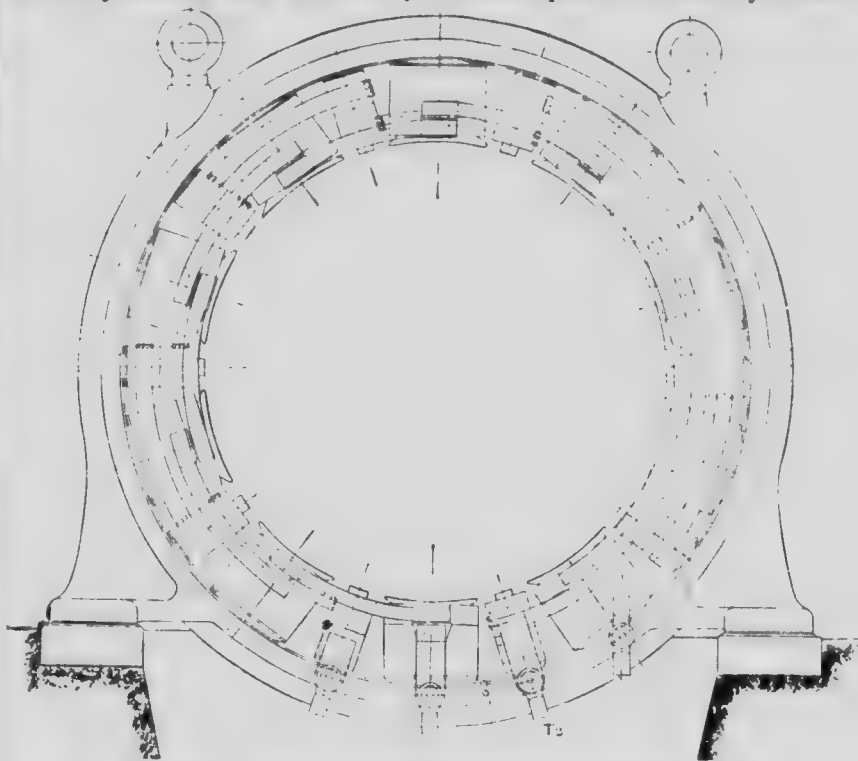


Fig. 11.—Diagram of Field Magnets of Mather and Platt 600-Kilowatt Multipolar Dynamo.

With the exception of machines similar to that illustrated in Fig. 511, Vol. I., which were never very widely used, the general plan for continuous current dynamos is to place the magnets outside the armature in the form of a continuous encircling yoke, with inward polar projections carrying the magnetising coils, and frequently having specially shaped pole faces attached. A good example of such an encircling yoke is seen in Fig. 10, which shows the yoke ring of a ten-pole machine built by Messrs. Mather and Platt for the Corporation of Salford a few years ago. This dynamo gives 800 kilowatts at pressures varying from 440 to 550 volts, the speed being 100 revolutions per minute. The yoke ring is of cast steel, cast in two parts,

being divided across the horizontal diameter. It is supported by the two side brackets which form part of the lower casting, the greater portion of which is sunk below the level of the floor of the dynamo room, thus reducing the height of the pedestals which carry the shaft. Since the joint between the inwardly projecting polar cores and the yoke ring cuts right across the magnetic circuit, shallow projections are cast on the ring, and

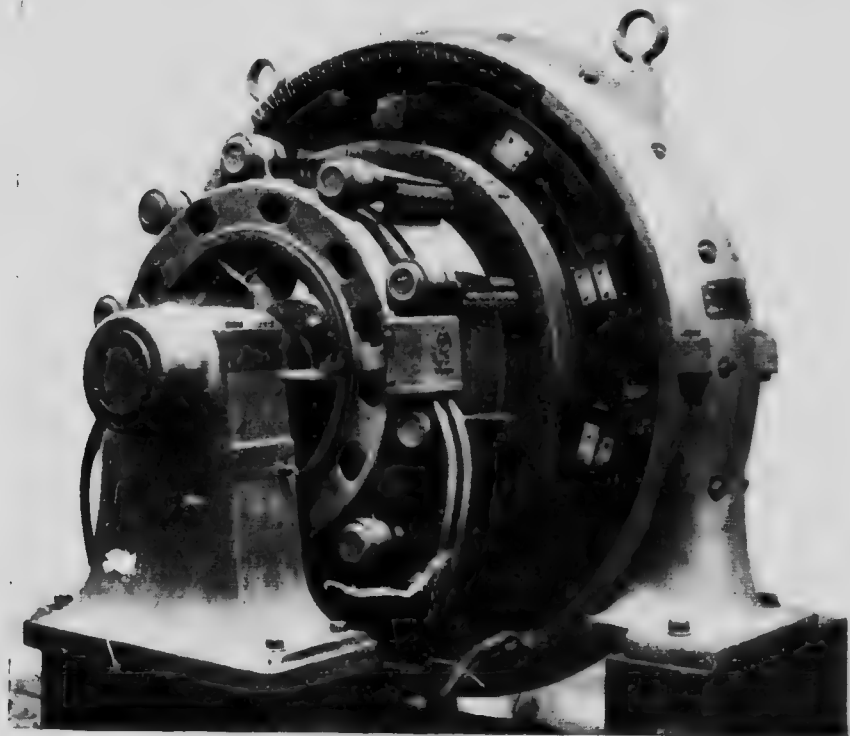


Fig. 12.—Mather and Platt 500-Kilowatt Multipolar Dynamo.

both sides of the joint are accurately machined, so that when bolted up it may be as mechanically perfect as is possible, and its magnetic reluctance reduced to a minimum. The figure shows the bolt holes used for fixing the cores, which, with their coils, can be withdrawn for examination without disturbing the rest of the machine.

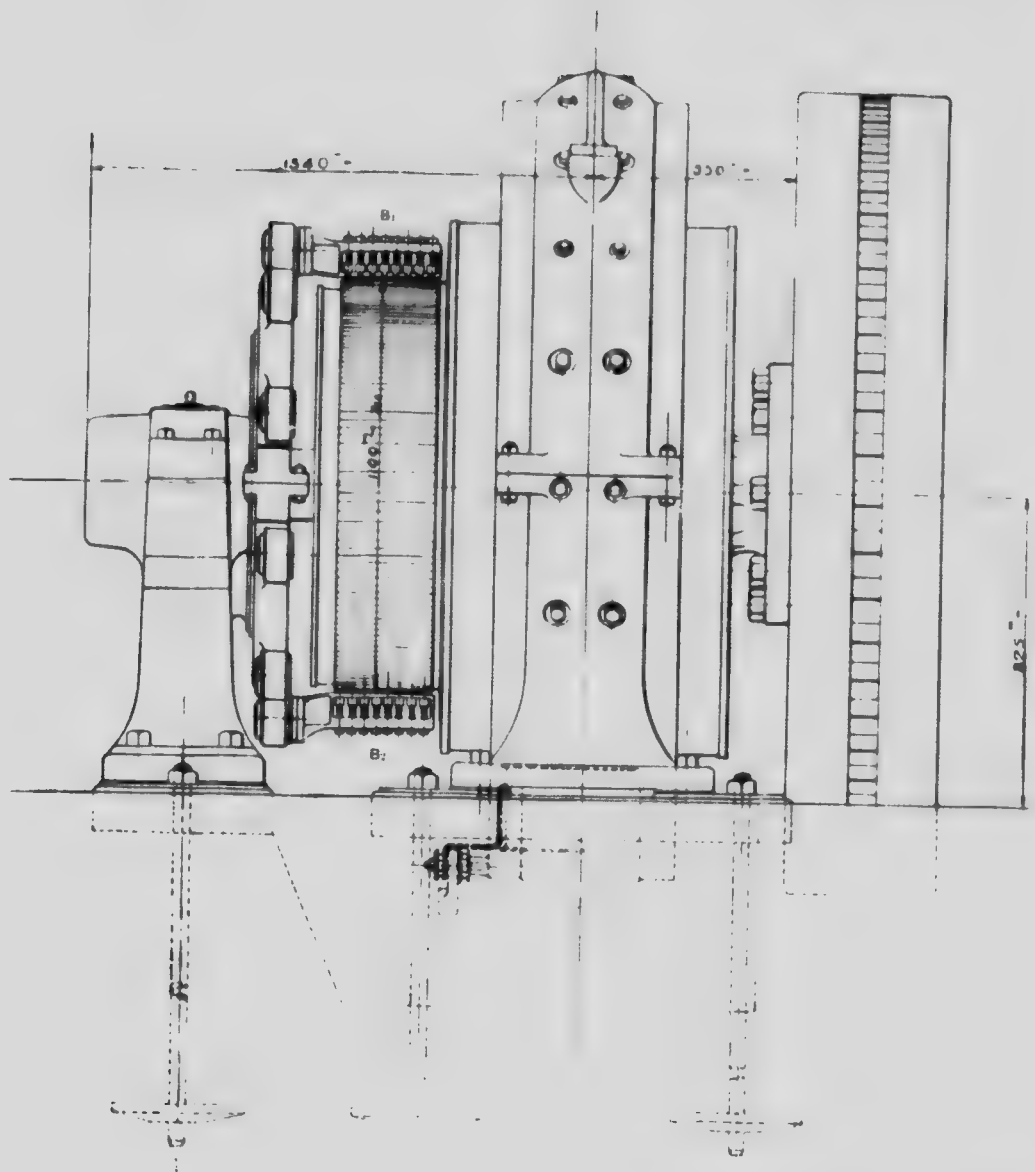
Particulars of a more modern but smaller machine by the same firm are given on Plate II., and in Fig. 11. This machine is a 600-kilowatt machine, running at 300 R. P. M., and giving a pressure of 550 volts. Though its outer surface is somewhat different and neater, the encircling yoke is

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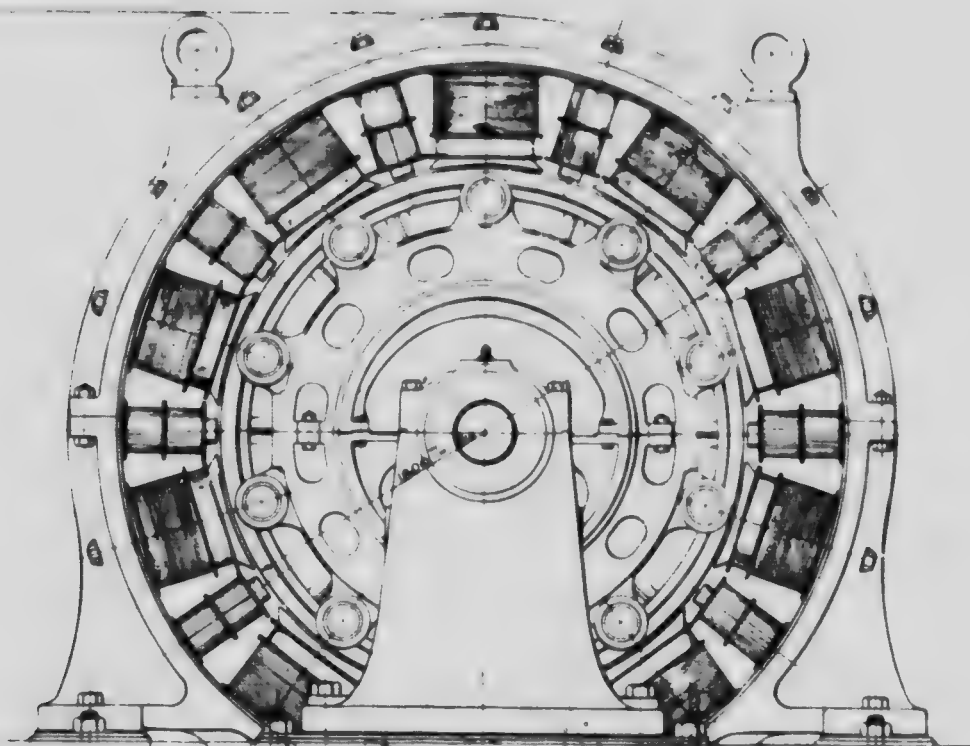
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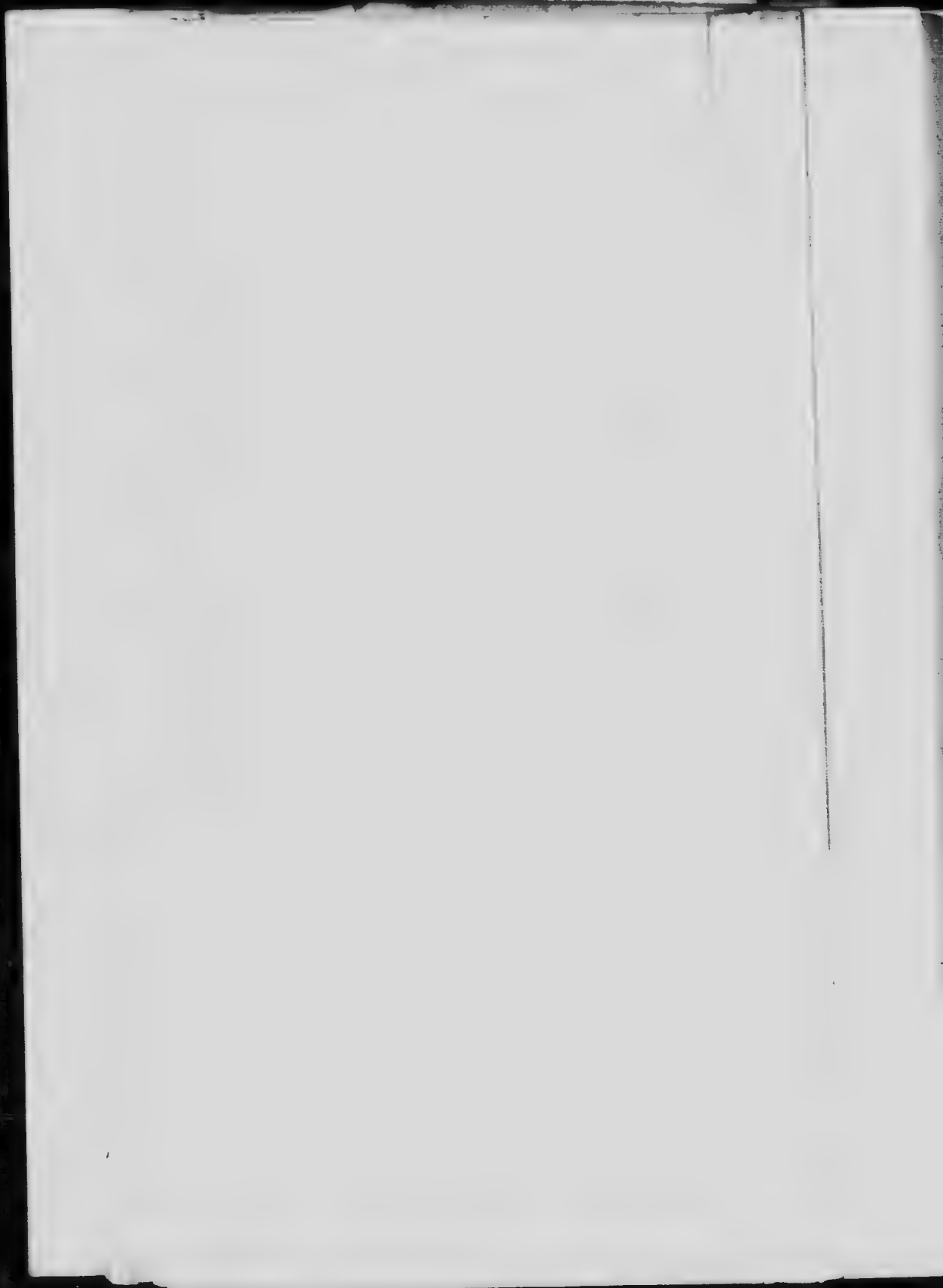
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in many respects very similar to that shown in Fig. 10, with the important difference that it not only carries ten main cores as there shown, but also the cores of ten interpoles whose function will be explained later (see page 107). It is therefore a compound-wound multipolar machine with commutating poles; the complete machine is shown in Fig. 12.

Some of the principal dimensions are marked on Plate II., and it will be noticed that, although the over-all diameter of the machine is 6 feet 11 inches, it is so far sunk that the axis is only 32.5 inches from the floor, and the pedestal supporting the left-hand bearing is correspondingly shortened. At the other end of the shaft is a half-coupling cast with the spider to couple directly to the engine fly-wheel, which is shown in position. The current is collected by ten sets of brushes B_1, B_2 , which lead to two conducting rings, ingeniously shielded by a bell-mouth guard attached to the pedestal, five sets of brushes being connected to each ring. Carbon brushes are used, there being eight of these on each brush arm. There are therefore 40 brushes for each ring, and at the full load each will take charge of 27 to 28 amperes, the current density not exceeding 30 amperes per square inch. There is no hand wheel to adjust the brush rocker, as the machine will run sparklessly at all loads, and up to 50 per cent. overload, with a fixed position of the brushes. Should it, however, be necessary at any time to readjust the position of the brushes, the bolts fixing the two halves of the brush rocker can be slackened, and the whole of the brush gear moved to a new position and fixed there. From the collecting rings the current, of 1,000 amperes at full load, is led by heavy flexibles to the terminals T_1, T_2 , which are placed in the pit below the dynamo so that the heavy conductors which carry the current to the switches, etc., on the switchboard may be conveniently run, and be out of the way of the moving machinery and of appliances which may be required in the event of a breakdown. Further details of this dynamo will be given later.

An example of a multipolar field-magnet casting is shown in Fig. 13, which was the pattern used by the British Westinghouse Company a few years ago for their six-pole railway generators, and is a good example of an interesting method of construction. The casting is divided into two parts across the horizontal diameter, the junction surfaces being carefully machined so as to fit well together when bolted up, for they cut perpendicularly across the magnetic flux. In this case the cores and pole faces of the magnets are of laminated soft steel, and are cast solidly with the yoke, as shown for another machine in Fig. 18, so that the only mechanical joints in this part of the magnetic circuit are the two already mentioned. There is, of course, a certain break of continuity from the cast iron to the mild steel, but as the former shrinks tightly on to the latter in cooling, the joint is probably better, from a magnetic point of view, than the best

machined surfaces can produce: The shapes of the stampings for such cores will be referred to later (see page 24).

As a further example Fig. 11 gives a picture of a large multipolar



Fig. 13.—Magnet Carcase of Westinghouse Multipolar Dynamo.

field magnet built by Messrs. Crompton and Co. The machine is a 14-pole machine designed for an output of 500 kilowatts when running at 150 R. P. M. Although somewhat hidden by the inwardly projecting

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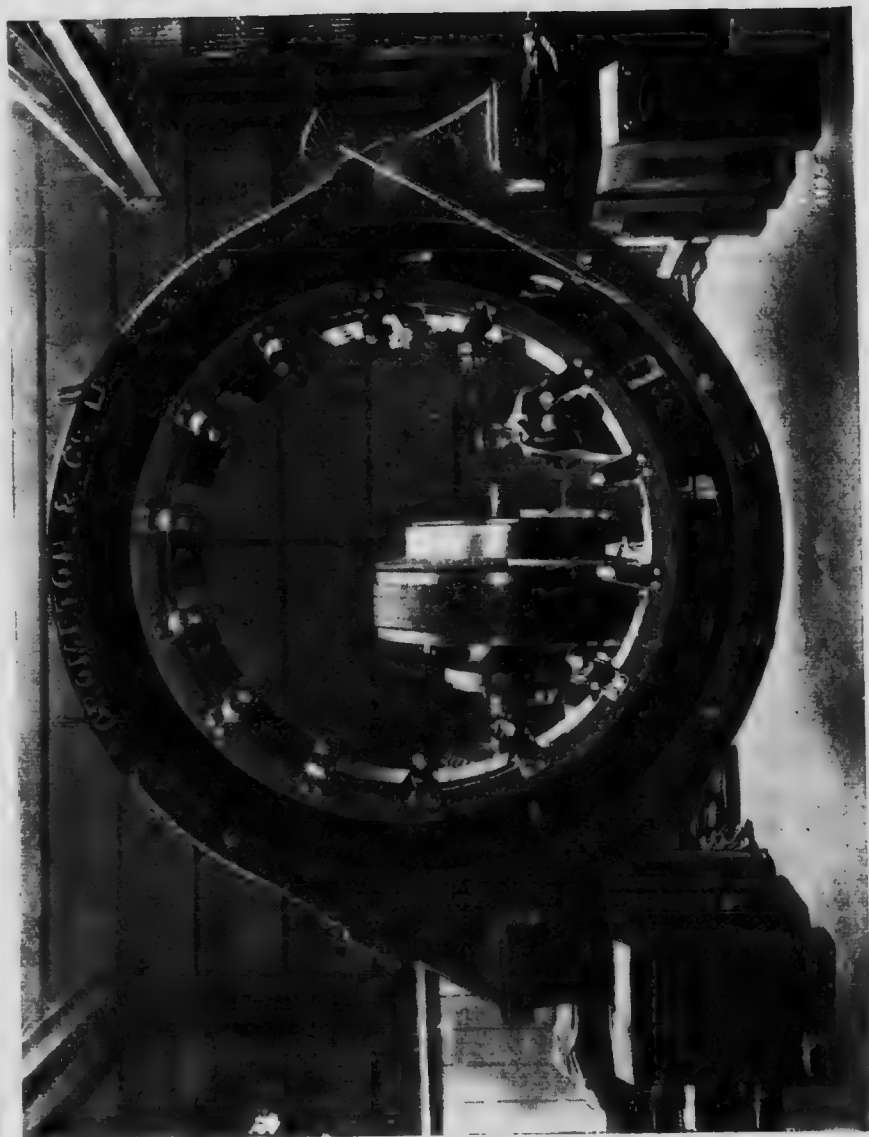


Fig. 14.—Crompton 500-Kilowatt Magoet Ring and Armature

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brackets which carry the brush ring, the shape of the poles and the pole faces can be easily made out. The armature of the machine can also be seen in the background. The over-all height of the magnet ring is 12 feet 6 inches, and the armature is 96 inches in diameter.

Most of the details of the construction of the magnetic circuit of this machine can be inferred from Plate III., which appears later, and which

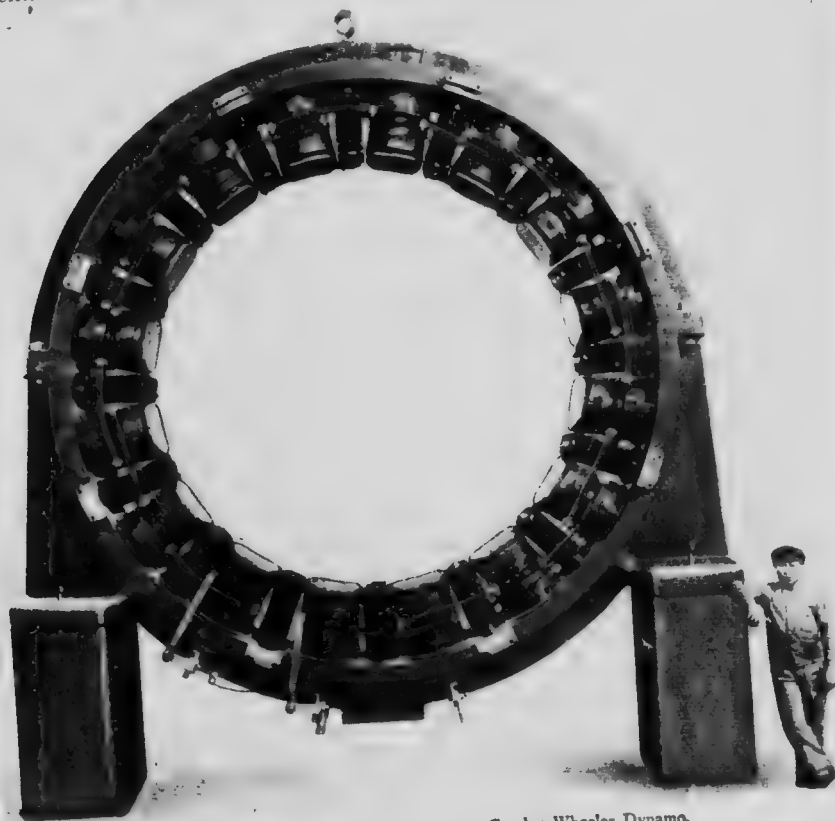


Fig. 15.—Magnet Ring of 1,200-Kilowatt Crocker-Wheeler Dynamo.

gives sections, etc., of a 750-kilowatt ten-pole machine of similar construction but with a smaller armature, 72 inches in diameter, running at the higher speed of 250 R. P. M. From this plate the method of carrying and clamping the core plates of the armature, and the shape of the cores and pole shoes of the field magnet, can be more readily made out. The cores are laminated and bolted to the yolk by steel screws.

To conclude this portion of the subject, and to enable our readers to compare American with English practice, we give, in Fig. 15, a picture

of the field magnet of a 16-pole machine built by the Crocker-Wheeler Company at Ampere, New Jersey, U.S.A. The field magnets are part of a machine which is designed to give an output of 1,200 kilowatts, 4,800 amperes at 250 volts, at a speed of 85 R. P. M. It is interesting to note that, in order to avoid the interpoles, the splitting of the yoke ring for constructional purposes, both in this and the Mather and Platt dynamo on Plate II., is made a little above the horizontal diameter, and that therefore the upper and lower sections are unequal. In Fig. 14 the yoke ring and supporting brackets of the 500-kilowatt Crompton dynamo appear to be cast in one piece.

Details of Field-Magnet Construction.

The actual settlement of the details and dimensions of the field magnets for a particular machine requires that the general principles laid down in the pages of Vol. I. should be carefully borne in mind, and involves also a fair amount of numerical calculation to insure that the output of the machine under the conditions of working shall be as specified. It will be well to

postpone the consideration of the main details of the calculations to a special section (*see infra*), but a few remarks of a general character may be conveniently introduced here.

Shape.—The cores of the field magnets should have an ample cross-section to carry the maximum flux required at the best working density, a point to which reference will be made again later. Of the various forms of cross-section which may be used, the circular is the most economical for the magnetising coils, as it has the shortest periphery for a given area enclosed. In Fig. 16 is given a series of figures, all of the same cross-sectional area. The number attached to each figure gives the length of the boundary line, that of the circle A being taken for convenience as 100. The next in order is the rectangle B, with semicircular ends and a perimeter of 106; then comes the square C, whose perimeter is 113. In D we have two circles

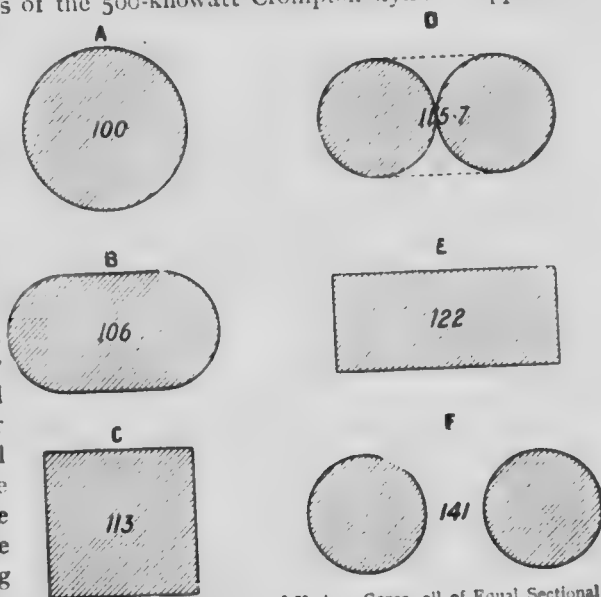


Fig. 16.—Relative Peripheries of Various Cores, all of Equal Sectional Area.

touching one another, but enclosed in a single turn of wire, as shown by the dotted lines, this turn will be 115.7 long. Then we have an oblong E with its length equal to twice its width, which gives a perimeter of 122, and last of all two circles F, each to be wound with its own magnetising coil a single turn of which will be 70.5 long, and therefore 141 will be required for the two circles. Some examples of cross-sections of cores have already been given, and some will appear later.

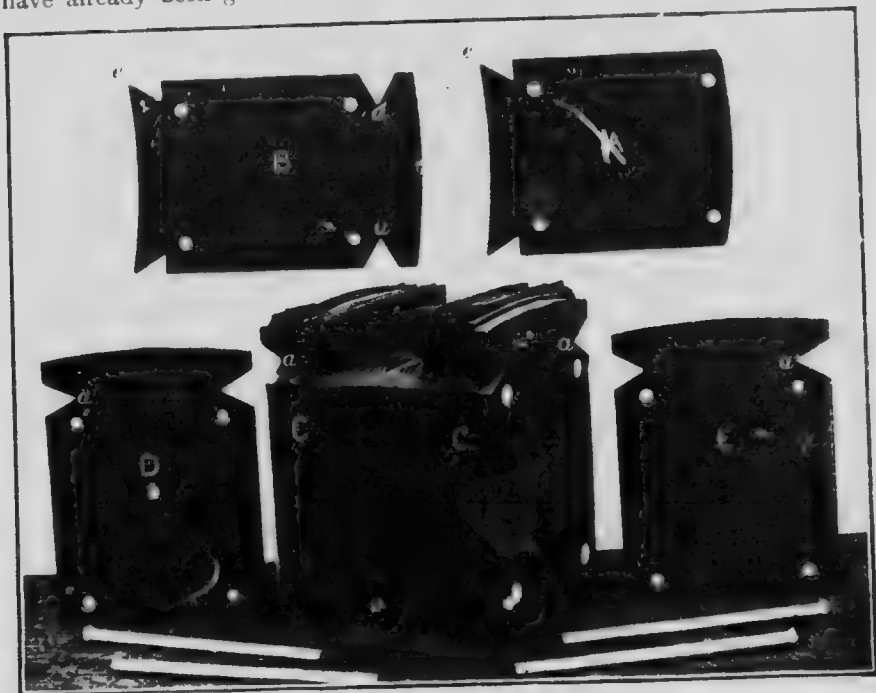


Fig. 17.—Details of Laminated Magnet Cores.

In the design of the magnetic circuit *sharp edges and corners* should be avoided, especially at places not far apart, between which the difference of magnetic potential is great and a leakage field readily set up. For reasons similar (*mutatis mutandis*) to those which have been dealt with in connection with the electrostatic field (see pages 82-84, Vol. I.), the lines of magnetic flux in passing from good magnetic to non-magnetic material tend to crowd together at places where the curvature of the surface is great. Sharp edges, therefore, tend to increase the leakage from the material on which they are placed. For particular purposes this may sometimes be desirable, but such cases are exceptional, and more usually the general rule should be observed.

The shape of the cores used in the large railway generators built by Messrs. Dick, Kerr and Co. is shown in Fig. 17. For several reasons, which will be dealt with in due course, it is found advisable to laminate these

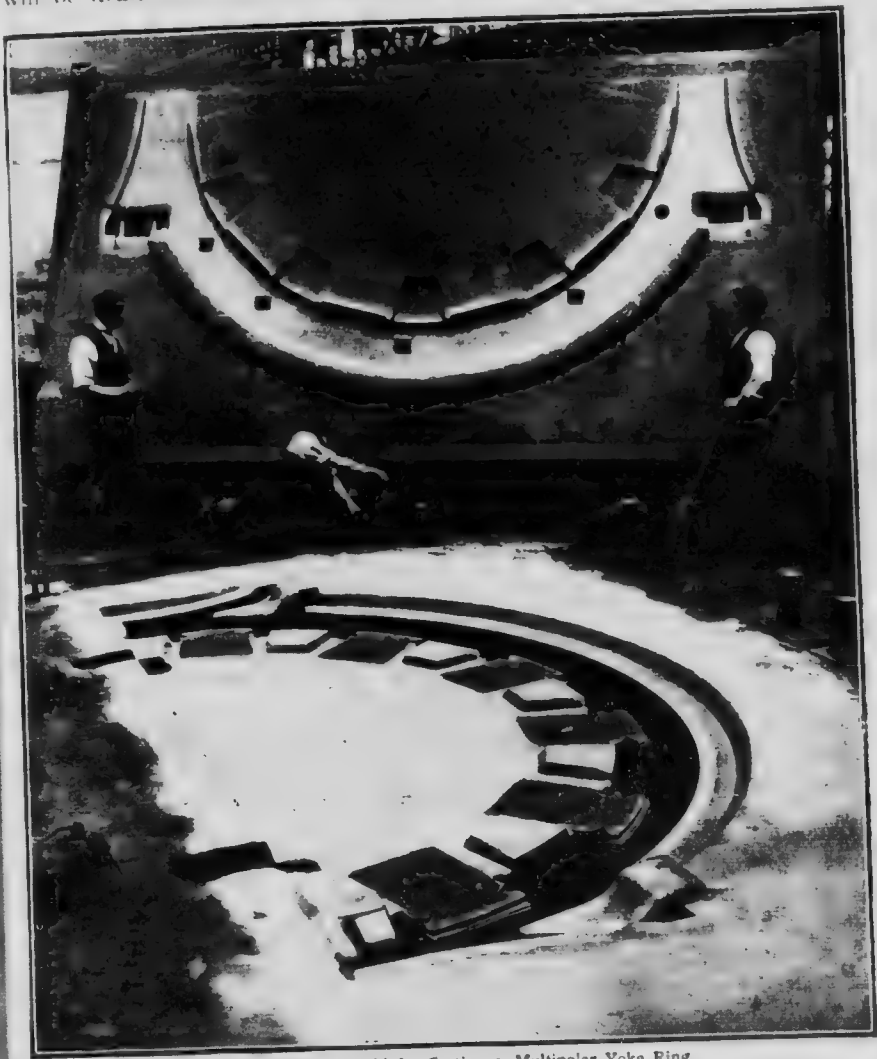


Fig. 18.—The Mould for Casting a Multipolar Yoke Ring.

cores, and the figure shows at A and B two patterns of sheet metal stampings which are used to build them up. The assembled stampings are shown at C C, where it will be noticed that the A stampings are in

the middle and the *B* stampings at the end. The top part of this figure *c c* is the part round which the molten iron is to flow in the castings, and the irregularities in the heights of the different sheets, as well as the undercut surfaces at *a a*, are designed with a view to enable the molten metal to key well into the parts of the core, making a good joint both mechanically and electrically. The thick plates *D* and *E* are the end plates, which can be seen in position on *c c*. The bolts used for bolting up are shown in front: they are lightly insulated from the laminated iron. The sharp edges at *e e* in the stampings are modified by having polar extensions

clamped round them after they are placed on the machine.

Some details of the preparation of the mould for casting the lower half of the yoke ring are shown in Fig. 18, where in the bottom part the core stampings will be seen imbedded in the moulding sand with their back ends projecting into the cavity



Fig. 19.—Magnet Frame with Exciting Coils.

into which the molten metal will be run. These projecting ends are coated with a suitable flux to ensure the union of the molten iron with the steel. When the upper part of the figure is placed over the lower part the mould will be complete. The whole magnet frame, with some of the magnetising coils in position on the cores, is shown in Fig. 19. One disadvantage of laminating the core of the field magnet is that it necessitates a nearly square or rectangular section, which, we have seen, is uneconomical for the magnetising coils. This consideration leads some manufacturers to use a cylindric solid core, and to confine the laminations to a specially shaped polar face. On the other hand, this necessitates an additional joint in the magnetic circuit, and a compromise has to be made between the conflicting conditions. Some makers (e.g. the Crocker-

Wheeler Company) cast the yoke round their solid cylindric cores in the same manner as above described for laminated cores.

Joints.—The above method of casting the cover with the yoke is not merely a matter of mechanical convenience, but has also certain magnetic advantages. Any break of continuity in the material, if so placed that the magnetic flux must cross the break, will manifestly add to the reluctance of the circuit, and should therefore be avoided if possible. In certain designs, however—for instance, where cast-iron yokes are used with wrought-iron cores, or in large multipolar yoke rings (see Figs. 10 to 15 and elsewhere)—there are manifest advantages, mechanical and otherwise, to be obtained by allowing such joints to exist. It therefore becomes important to inquire how far the reluctance is increased, and how such increase may be minimised.

Experiments have been made with this object by Ewing and others, and it has been found in the first place that a badly fitted joint placed across the flux in a magnetic circuit adds considerably to the reluctance, but the ill effects may be reduced by carefully machining and fitting the two sides of the joint so that they come well together.

The other factor which affects the reluctance of the joint is the flux density B . This is due to the fact that the magnetic flux causes an attraction between the surfaces, the pressure thereby created being proportional to B^2 . As the surfaces thus become magnetically more tightly held together we should expect the reluctance of the joint to diminish, and such is, in fact, the case. With some experiments with wrought iron it was found that with a flux of about 1,500 gaussess* the reluctance of a well-machined joint was equal to that of 3 inches of the solid iron; at 12,400 gaussess the reluctance fell to that of 1 inch of solid iron; whilst at 18,200 gaussess it was as low as 0.005 inch, and at still higher densities the difference ceased to be appreciable. Thus at high flux densities a well-machined joint had no appreciable effect, but at low densities the effect was very marked.

One other point is worth notice, and that is that when the joint is between materials of different permeabilities the extent of the contact surface should be calculated for the material of lower permeability. The reason for this is obvious. The reluctance of a joint between different materials may be diminished by casting one round the other.

Magnetic Balance.—Connected with shape is the question of balancing the magnetic pulls between armature and field magnet. The so-called magnetic flux from the iron of one to the iron of the other is only a convenient way of representing the strains in the medium and the resulting mechanical forces. If everything is perfectly symmetrical, the pulls on one side of the axle will balance the pulls on the other, and no additional

* That is, 1,500 magnetic lines per sq. cm.

strain will be thrown upon the bearings. But if there be any want of symmetry in the fluxes at different parts there may exist unbalanced forces, which may cause serious trouble.

Take, for instance, the case of an overtype dynamo such as the one a part of whose magnetic circuit is given in Fig. 20. With perfectly uniform air gaps the magnetic flux across the lower halves of the gaps will certainly be greater than the flux across the upper halves, because of the shorter length of magnetic path through the lower half of the armature. In this case the armature will be pulled downwards with greater force than it is pulled upwards by the magnetic actions in the lower and upper halves of the gaps, and the lower linings of the bearings may suffer in consequence, thus increasing the mischief because the diminished air gap thus produced opposite

the lower part of the armature will, in its turn, give rise to a still further increase in the flux.

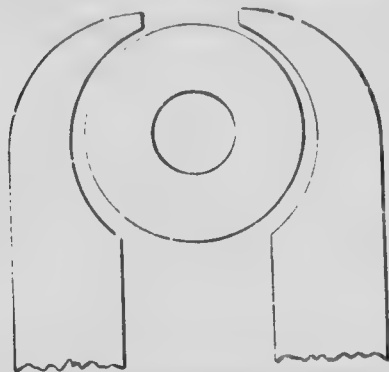


Fig. 20.—Armature Decentered to Counteract Magnetic Pull.

Several remedies have been proposed. The simplest consists in deliberately decentering the armature by raising its axis above the axis of the cylindrically bored pole faces, as shown on an exaggerated scale in Fig. 20. In this way an attempt is made to counteract the additional reluctance of the iron in the paths which pass through the upper half of the armature by the diminished reluctance of the air gap.

In fact, the idea may be carried much

farther than mere balancing, and the flux made greater in the upper than in the lower half of the armature so that the magnetic pulls counteract the downward pull of the weight of the armature, which in special cases may be imagined even as floating in the interpolar space, the bearings merely acting as almost frictionless guides.

The case of unbalanced magnetic pulls in large multipolar machines is especially interesting, and will be returned to later. Also in regard to the whole design, as distinct from the details above considered, questions of commutation and armature reaction, which will be dealt with later, must be taken into account.

Magnetising Coils.—In modern continuous current machines the pole pieces and cores of the field magnets are usually so designed that the magnetising coils can be slipped into their places after being wound separately on dummies or "formers," as they are called. In some cases the pole face is simply an extension of the core without enlargement, and then the coils can be slipped over the end, but some kind of clamping device is

required to hold them in their places. Sometimes the pole face is larger than the core and is detachable; it is then finally put into position after the coils are in their places, thus serving the double purpose of a pole face and of a clamp for holding on the magnetising coils. Other methods will appear in the sequel.

The object of the magnetising coils, as already explained in Volume I., is to provide, under the various conditions under which the machine is required to run, the requisite number of ampere-turns of excitation to



Fig. 21.—Magnetising Coils of Westinghouse Dynamo.

give the flux through the armature necessary to produce the desired E. M. F. or the desired terminal P. D. This excitation, and therefore the required ampere-turns, usually increases with the load (as will be seen later when the question of regulation is being discussed), and this, as a rule, necessitates the use of two sets of coils—one, the *shunt* coils, consisting of many turns of a comparatively thin conductor supplied with current by the full pressure of the machine; the other, the *series* coils, through which the whole current, or nearly the whole current, generated passes. The latter, having to carry a heavy current, must necessarily be wound with a conductor of ample cross-section, but, *per contra*, a few turns of this conductor will give the necessary ampere-turns of excitation, because of the heavy currents traversing them. The two conditions are therefore not antagonistic.

A pair of magnetising coils for one of the magnet cores of a 500-kilowatt railway generator is shown in Fig. 21. In this figure the shunt or fine wire coil is in the front, and the series or thick wire coil behind it. The former has been carefully bound with cord after being wound. The latter is made up of heavy forged copper conductors whose massive rectangular section can be clearly seen in the figure. At full load the series coil would have to carry a current of about 1,000 amperes; the massive lugs by which this current is led into the coil can be seen on the right-hand side, contrasting sharply with the more modest lug *l* in front, which is sufficient for the current for the shunt coil. The construction of the light metal frames by which the coils are stiffened and held in their places on the dynamo can be readily made out.

A still more complete illustration of the details of field coils, as made

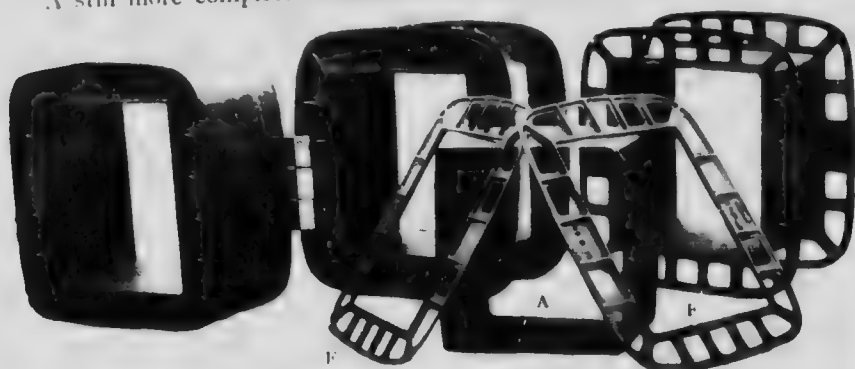


Fig. 22.—Magnetising Coils used by Messrs. Dick, Kerr and Co.

by Messrs. Dick, Kerr and Co., of Preston, is given in Fig. 22. The frame consists of a thin sheet-iron box *A*, with light end flanges *F F*, seen apart at the front of the figure. The complete frame *B* is on the extreme right, and the same, covered with the necessary insulating material, is in the centre. The fully wound coils are on the left, with the series and shunt lugs to form connections projecting from the side. The windings of the two coils cannot be distinguished, as the whole has been served with a binding layer of cord or other textile material.

In large multipolar machines with twenty or more poles, although the amount of energy required for excitation is not large, the available space is so limited that special devices have to be employed to utilise this space to the best advantage. One very ingenious method used by the General Electric Company, of New York, for meeting the difficulty in a 2,700-kilowatt 36-pole machine, is shown in Fig. 23*. The conductor consists of a copper strip *s*, carefully insulated, and placed edgewise on

* From the *Street Railway Journal* of New York.

the core *c* in a single layer of winding. In this manner the space occupied by insulation is reduced to a minimum, and, although the cooling surface is small, each turn of the winding has one edge on the outer surface, and, the energy to be radiated not being very great, the allowance for cooling

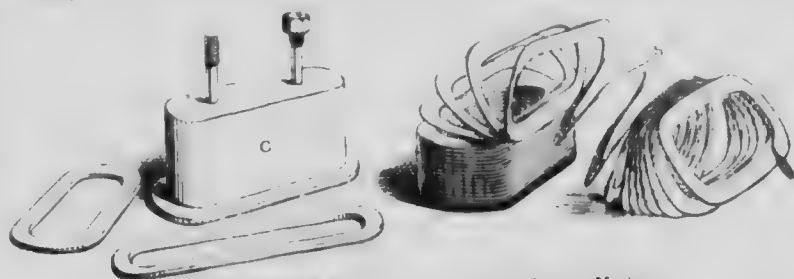


Fig. 23.—Shunt-Wound Field Coils for Large Multipolar Machine.

is found to be ample in practice. This method of winding field coils was described in the previous edition of this book, and has since been widely adopted where the conditions of the design render it desirable. The appearance of such coils when completely wound, but before being mounted, is shown in Fig. 24, taken from a photograph of two coils constructed by the British Electrical Engineering Company for a large multipolar dynamo.

In concluding this part of the subject, we give in Fig. 25 an illustration of the field magnet of a 10-pole dynamo as built by the Electric Construction Company, of Wolverhampton. It shows well the method by which the magnetising coils are held in position by webbed end

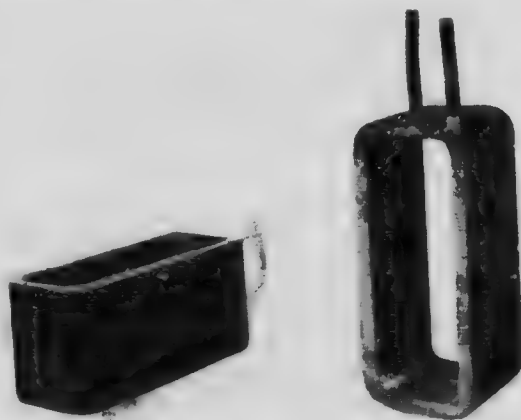


Fig. 24.—Field-Magnet Coils Wound with Flat Copper Strip.

plates, which are so constructed as to provide pole tips for the polar faces of the core, these pole tips being raked back so as to widen the air gap under them, for reasons to which reference will be made presently. In this case the series regulating coils are wound over the shunt coils, and not side by side as in Fig. 21, the connecting conductors are shown prominently. The particular machine of which this field magnet forms a part is intended to give an output at full load of 600 kilowatts at 250 amperes at 500

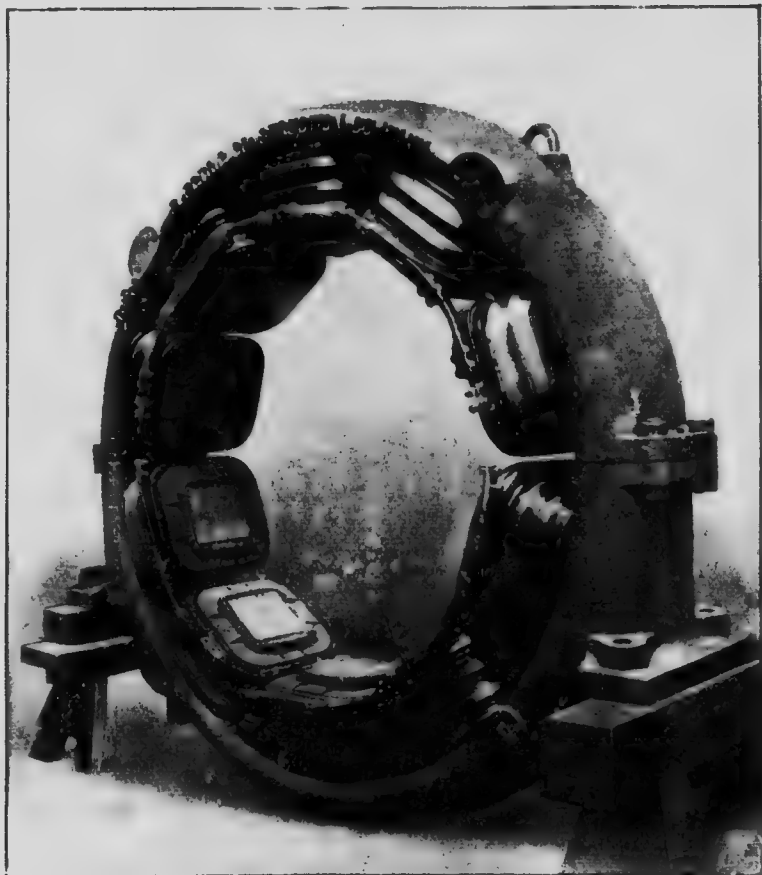


Fig. 25.—Electric Construction Company's Wound Field Magnet.

volts, when run at 280 revolutions per minute. Further details of field magnet design and construction will be given in connection with interpolar and other devices for dealing with the armature reaction and for improving commutation.

III.—THE MAGNETIC CIRCUIT; THE ARMATURE

The general plan of the part of the armature which is intended to carry the lines of force from pole to pole of the field magnet offers far less variety to the designer than the details of the field magnet part of the circuit. In most continuous current machines it consists of a hollow cylinder built up with laminated iron discs, and the chief differences between various designs relate either to the arrangements made for receiving the copper

conductors or to the particular method adopted for transferring in a good mechanical manner the driving torque from the axle to the iron discs.

It will be most convenient to deal here with the first of these details, as it enters directly into the magnetic part of the problem, and to postpone reference to the other points to the section dealing with "mechanical details." For this purpose ordinary ring- or drum-wound armatures may be divided into those with (a) *smooth* cores and (b) *slotted* cores. A third class (c), in which the copper conductors are buried in the iron, is usually applied to drum-wound armatures only; such cores are known as *tunnelled* cores.

(a) **Smooth-Core Armatures.**—The early form of Gramme armature (Fig. 464, Vol. I.) was of this type, the core consisting of a cylindrical ring of iron wires. Such a form of core, though magnetically best, because of the more perfect lamination, and more especially for ring-wound armatures of short axial length, is mechanically weak and difficult to drive satisfactorily when, as in modern machines, very considerable torques have to be provided for. Except for very small machines, therefore, it is now the custom to use thin sheet-iron stampings of forms somewhat similar to those in Fig. 26. The sheets used are frequently of good wrought iron, of the quality known as charcoal iron or of mild steel, in either case of high magnetic permeability. When the diameter is not too large to make the waste important, or when the waste pieces from the middle can be used for stampings for smaller machines, each stamping consists of a complete ring similar to A. The stamped ring has usually some provision for driving; in the figure three equidistant notches are shown, into which the arms of a driving spider will be fitted when the core has been built up. Sometimes holes through which bolts can be passed are used. For large machines the stampings, to avoid excessive waste, are in the form of segments of rings as at B (Fig. 26). Three bolt holes are shown, and in building up the core from the stampings care must be taken to "break joint" in successive layers—in other words, the radial lines *a*, *b* must be enclosed by the flat of the adjacent stampings on either side; if this precaution be not adopted, the finished core will be mechanically weak at these joints.

(b) **Slotted-Core Armatures.**—The earliest example of a slotted-core

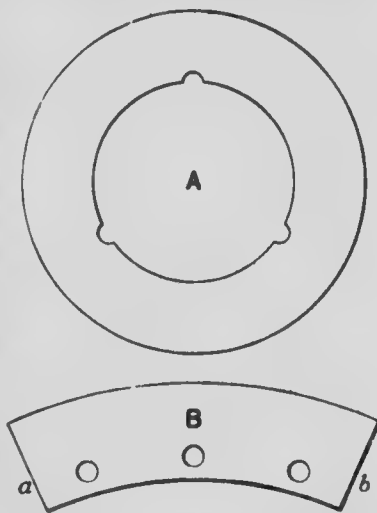


Fig. 26.—Forms of Smooth-Core Armature Stamping.

armature was Pacinotti's motor (Fig. 561, Vol. I.), constructed in 1861. There is little doubt but that Pacinotti adopted this form because of the ease with which the forces acting on the wires could be transferred to the rotating axle. The converse reason—namely, the good mechanical transference of the driving torque from the shaft to the conductors—has led modern constructors to adopt the slotted armature in a form differing very widely from that used by Pacinotti.

For reasons already set forth in Volume I. the core is built up of stampings from sheets of good iron or mild steel of high permeability. There is, however, in different machines, almost every possible variety of size, shape, and proportion given to the slots. In some machines they have straight radial sides, varying from shallow wide slots to narrow deep ones. In others the mouth of the slot towards the pole pieces is more or less closed, and within the space to which this narrow opening gives access the wire lies in a shallow or deep chamber, the shape of which differs widely in different machines.

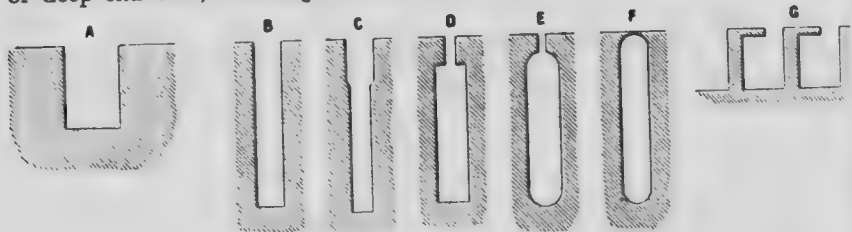


Fig. 27.—A Few Common Forms of Armature Slots.

Some of the shapes of slots in most common use are shown diagrammatically in Fig. 27. In A there is a simple straight-sided slot somewhat wide and shallow, whilst in B, though still straight sided, the slot is narrow and deep. Between these two and outside of them in both directions slots are used with many different proportions of width to depth. As an intermediate kind between the closed and open slots, C is a slot used by Sayers, the wide part containing his compensating coils and the narrow part his main windings. In D the slot, whilst still rectangular, is nearly closed by the iron projecting over it and leaving only a narrow opening, whilst in E the nearly closed slot has semi-circular ends. A tunnelled hole very similar to E, but with the opening completely closed, is shown at F; the iron towards the pole face closing the slot is, however, much less substantial. At G is shown a form of slot used by the Crocker-Wheeler Company for motors; this slot is partially but unsymmetrically closed. It is scarcely necessary to point out that slots similar to D, E and G tend by their shape to hold the conductors in their places and to counteract the effects of centrifugal force. A few ordinary forms of stampings for slotted-core armatures are shown in Figs. 28 and 29. In Fig. 28 J and K are stampings

with open rectangular slots similar to A and B of Fig. 27, though with different ratios of breadth to depth. The stamping M has also slots which are practically rectangular and are quite open; but it will be noticed that the ends of the teeth are undercut, the object being to provide grooves in the finished core into which wooden or other wedges can be driven after the copper windings have been placed in the slots, in order that these windings may be prevented from flying out radially from the slots when the armature is running with a high velocity. In Fig. 29 N and P are two stampings in the form of segments of rings, the slots being open and rectangular. These are standard stampings, supplied to dynamo manufacturers by Messrs. J. Sankey and Sons; they are for large machines, and are similar to the smooth-core stamping B in Fig. 26.

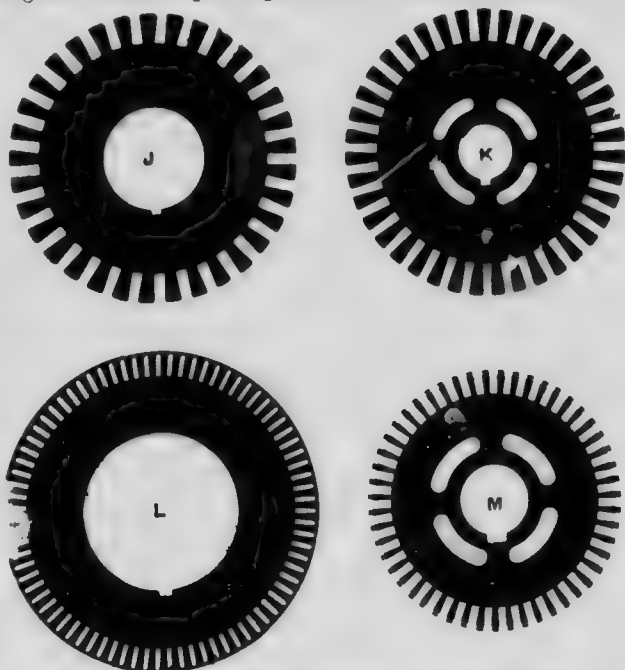


Fig. 28. — Forms of Slotted- and Tunnelled Core Armature Stampings.

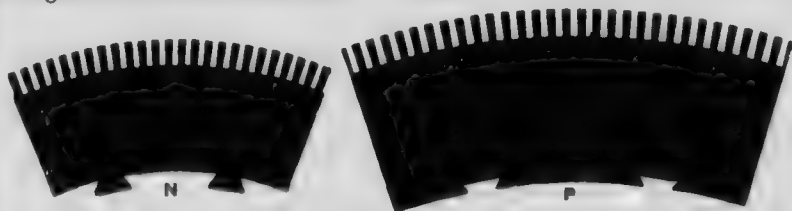


Fig. 29. — Segment Stampings for Slotted-Core Armatures.

It is instructive and important to notice how the sharp curvature of the armatures, for which the stampings J, K and M of Fig. 28 are intended, necessitates a very perceptible narrowing of the teeth at their bases. This narrowing appreciably increases the flux density and lowers the permeability

at the base of the teeth when the machine is fully excited. On the other hand, in the segmental stampings of Fig. 29 the teeth as well as the slots are practically, though not quite, rectangular. Other examples of the shapes of slots in actual use will occur in connection with illustrations of particular machines.

(c) **Tunnelled-core Armatures.**—These scarcely need separate consideration, for as regards mechanical details they are the toothed armatures with the faces of the teeth overlapping until they meet and close up the slot completely. In Fig. 27 F, a diagrammatic sketch of one of these holes is given, and in Fig. 28 I shows an actual stamping for a tunnelled-core armature in which the thinness of the iron which closes up the slot should be noticed. When building up the core, the holes if already stamped must be placed accurately in line, and even then may have to be tooled before the insulating lining and the conductors are introduced. Another but more costly way of attaining the desired result is to build up the core with plain sheets, and then drill out the necessary holes.

Smooth v. Slotted or Tunnelled Cores.—We can now examine briefly the reasons for the great variety shown in the construction of what is initially so simple a thing as the core of a continuous current dynamo. It may be premised that, since most of the forms referred to are widely used, there is no overpowering reason for the use of one rather than another. In fact, they each represent a compromise of conflicting conditions, and, according to the special circumstances of the case, sometimes one form, sometimes another, is adopted by a dynamo designer.

Slotted and tunnelled cores have two great advantages over smooth cores. In the first place the non-magnetic gap in the circuit is diminished by bringing the iron of the core more or less near to the iron of the pole piece. This advantage obviously diminishes as the flux increases and the teeth become saturated; but even at high densities in the teeth their permeability is still much greater than that of the neighbouring non-magnetic materials. The second great advantage is the positive driving of the conductors in the slots or tunnels, for it is clear that the driving force can be more readily transmitted to a conductor lying in a slot in the core than to one lying on the outside of a smooth core. Not only are the conductors better placed for driving purposes, but being screened magnetically by the teeth the forces acting on them are less, the greater part of the drag being taken up by the core. We have seen (page 592, Vol. I.) that the force acting on a current-carrying conductor placed in a magnetic field depends upon the intensity of the field. In a slotted armature the greater part of the flux passes through the teeth, and less and less through the slot as the latter becomes more and more closed. Consequently, although the full currents are flowing through the conductors, the forces acting on the latter are not so great as in a smooth-core armature, in which the whole flux passes through the active wires.

As minor advantages may be mentioned the fact, due to the cause just named, that the tendency for the formation of eddy currents (*see* page 60) in the conductors is so diminished that in tunnelled armatures solid un-laminated bars of copper can be used. Further, arrangements for ventilation can be more easily made in slotted armatures, and the armature is kept cooler because of the extra radiating surface of the teeth.

On the other hand, the teeth, as they sweep past the polar face, cause oscillations of the magnetic flux in the iron near the surface. Fig. 30 shows in a rough diagrammatic way how the lines in the pole piece *P P* tend to crowd towards the nearest teeth *T T T*, and to be less dense opposite the slots. The actual disturbance of the flux in the pole shoe is more accurately shown in Figs. 43 and 44, page 57, in which the real distribution of the lines is depicted. This fluctuation of the magnetic lines will give rise to eddy currents in solid pole faces, and a consequent loss of energy. Hence, in some modern dynamos the pole faces are laminated, and in others (*see* Fig. 17) the whole magnet core is laminated. The losses due to these eddy currents may also be diminished by increasing the number of teeth and by shaping the outer end of the tooth so as to overlap the slot.

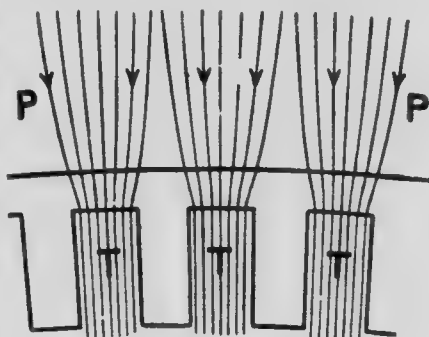


Fig. 30.—Effect of Teeth on Pole Flux.

Also in toothed armatures the coils, being well imbedded in iron, have greater inductance than similar coils on smooth cores; in consequence, sparkless commutation, as we shall see presently, is not so easy. As minor disadvantages may be mentioned that, on account of the high flux density, the hysteresis loss due to the reversals of the magnetism in the teeth will be greater, and there will be increased leakage through the core outside the windings, the latter more especially in tunnelled armatures. This increased leakage tends to diminish the gain obtained by the lessening of the excitation ampere-turns due to the lower reluctance of the air gap.

In general therefore, we may say that for traction dynamos and motors the advantages of the slotted core, under the conditions of working, far outweigh its disadvantages, and it is universally used. At the other end of the scale, for low-voltage machines with heavy currents to commute, the disadvantage of the high inductance of the short-circuited coils in the slotted cores causes the preference to be given to the smooth core by many manufacturers. Between these extremes each case has to be dealt with on its merits.

Lamination.—The reasons why the *core of the armature of a continuous current dynamo* should be laminated have already been given (*see* page 400, Vol. I.), and it has been pointed out that the laminations should be "at right angles to the currents in the coils, and parallel to the direction of motion." For drum-wound armatures or for ring-wound armatures in which the length parallel to the axis is at least several times the radial depth, these conditions are attained by using thin discs of metal of the proper shape threaded upon the axle and lightly insulated from one another. But when the ring-wound armature is short compared with its radial depth, so that when wound it approaches the shape of a disc and therefore has the longer length of the conductors radial instead of parallel to the axis, it is obvious that the laminations should be as nearly as possible in concentric cylinders. This can be attained by building up the core with successive layers in the form of narrow hoops or ribbons of iron. A well-known example is the core of the Brush arc-lighting machine, already illustrated (*see* Figs. 468, 469, 470, Vol. I.). In the Mordey-Victor dynamo also (*see* Fig. 500, Vol. I.) the laminations are circumferential instead of radial for the same reason.

In order that the eddy currents which may be set up within the iron sheets should be negligible, it is essential that the sheets should not be too thick. At the same time it is mechanically necessary that they should have a certain amount of rigidity. These conflicting conditions are adjusted by using sheets of from $\frac{1}{2}$ to 1 millimetre in thickness, or, in English measure, from 20 to 40 mils* thick. To increase the stiffness, the two outside discs are often thicker, say, from 150 to 190 mils, though in some cases they do not exceed 50 mils.

Since the E. M. F.'s which tend to drive currents across the laminations are quite small, only very moderate insulation is necessary, and since the insulating material is usually non-magnetic it is important to reduce the space it occupies to a minimum, for the laminations lie in the direction of the magnetic flux, and therefore occupy very valuable space. The materials generally used are either varnished paper, thin enamel, japan, oxide of iron, asbestos paper, etc. The oxide which forms on the surface during annealing is relied upon by some manufacturers, with only the addition of a sheet of paper every four or six plates. The amount of magnetic space occupied by the insulation depends on the material used and the thickness of the core discs. It varies from about 5 per cent. with oxide of iron to about 20 per cent. with enamel if very thin discs are used. In the latter case the space occupied by the non-magnetic insulation is a very appreciable fraction of the whole cross-section.

Apart from the armature cores it is desirable, in most cases, that the other iron parts of the magnetic circuit of continuous current dynamos

* One mil = $\frac{1}{1000}$ th inch.

should be of solid iron. This has the effect of steadying the magnetising current, and therefore the magnetism, since whenever the flux begins to change "eddy" currents will be set up in the mass of the iron, and these will retard the change. It is instructive to note the length of time which it takes a massive field magnet to "unbuild" when a large machine is being put out of action.

In some cases, however, especially in connection with sparkless commutation and where rapid changes of load have to be provided for, it

is considered desirable to laminate the pole pieces; and in multipolar machines the cores of the magnetising coils, when these are continued to form the poles, are also frequently laminated. In turbo-dynamos even the yokes are sometimes laminated. Examples have been already given, and we shall return to the subject again later. It is perhaps needless to point out that the magnetic desirability of a solid core and yoke much simplifies the mechanical construction.

Ventilation.—Since heat is generated in the conductors of the armature at a rate depending on the resistance and the square of the current, and since, because of the reversals of magnetisation, further heat is generated in the iron core by hysteresis at a rate depending on the speed and the quantity and quality of the iron, it is necessary to provide efficient means for disposing of this heat by radiation, convection and conduction if the temperature of the armature is to be kept within reasonable limits.

In fact the facilities for getting rid of this heat determine largely the load the machine can carry:

In slotted armatures ventilating ducts are provided at intervals when

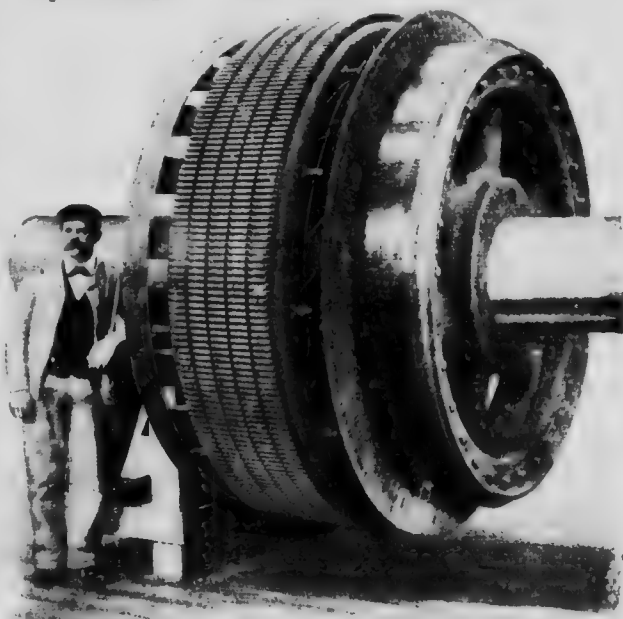


Fig. 31.—Unwound Multipolar Armature, with completed Commutator.

building up the core discs: They appear in most of the figures of armatures which are given in these pages, but attention may be specially called to Fig. 122, in which two such ventilating rings are clearly visible, being formed by placing small distance pieces at intervals between the discs.

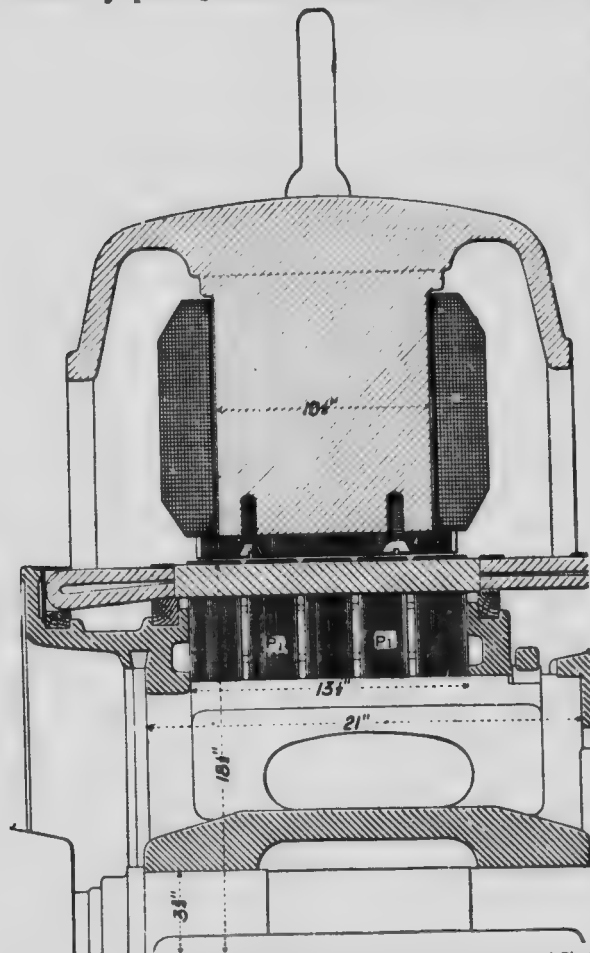


Fig. 32.—Longitudinal Section through a Magnet Pole, Armature and Shaft, showing Ventilating Ducts and Armature.

The completed armature carcass ready to receive the windings is illustrated in Fig. 31, in which four such annular ventilating spaces appear. These spaces are crossed, and therefore to a certain extent closed, by the copper conductors, but this is no disadvantage, as the cold air rushing past the heated conductors tends to keep them cool. For other examples of ventilating ducts the reader is referred to Figs. 567, 596, 597 and 618 in Vol. I., and other figures in which armatures appear later in this volume.

The ventilating ducts are also well shown in Fig. 32, which is a half-section through a magnet pole and the armature core of a dynamo, built by the International Electrical Engineering

Company. The core plates $P_1 P_1$ have an axial length of 13.5 inches, and the ducts are less than 2.5 inches apart. The drawing also shows how the plates are clamped on the driving spider, on which they also key.

In order to construct these radial ventilating ducts some form of distance-piece is necessary to hold the core plates apart on either side

the duct. Much ingenuity has been shown in designing these distance-pieces, which usually take the form of attachments to or projections from a stouter stamping than the ordinary core plates. One of these arrangements, designed by Messrs. Mavor and Coulson, is shown in Fig. 33: the distance pieces are thin tubes of sheet iron placed behind each tooth of a stout core plate, and projecting radially inwards.

In all these cases the mere rotation of the armature will expel air by centrifugal action from the ducts at the circumference, the place of the expelled air being necessarily taken by colder air, drawn in through the open spaces at the ends of the armature. Internal ducts parallel to the

axle are provided in stampings K and M of Fig. 28. They are intended to allow for the passage of cold air from the ends of the armature to the intermediate radial ducts. No such passages are provided in stampings J and L of the same figure, and these patterns of stampings should therefore only be used for smaller machines. The longitudinal ducts are not shown in Fig. 33, which is an illustration of the distance pieces only; but it must be understood that such ducts must be provided if advantage is to be taken of the cooling effect of radial slots.

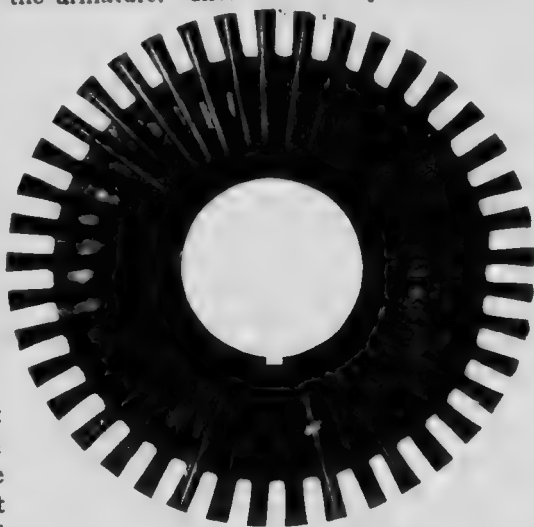


Fig. 33.—Core Plate with Distance Pieces.

In some armatures the centrifugal action in creating a current of air is assisted by the arms of the driving spiders or by the end connections being specially shaped, or by pieces of metal inserted to produce a fan action tending to drive air towards the ventilating ducts. In Messrs. Bruce Peebles and Co.'s dynamos (*see* Plate I.) the ventilating ducts are exceptionally wide, and in them are placed cast-iron plates with radial projections on both sides, so shaped that when the armature revolves they act as fan blades and drive air through the ducts on to the conductors. These plates are keyed on to the driving spider in exactly the same way as the core discs amongst which they are placed. By these means the machine is either kept cooler or may carry a heavy overload for a longer period without getting dangerously hot.

In smooth-core armatures the copper conductors, in which a large proportion of the heat is generated, are better exposed to radiation; but, on the other hand, the iron core is more completely covered in. It is, therefore, more difficult to arrange for effective ventilation, as most of the heat has to be radiated from the outer surfaces.

As regards winding, ring-winding, as a rule, offers greater facilities for radiation than drum-winding, and therefore may be worked at a higher current density. It must not be overlooked that both iron and copper are good conductors of heat, especially the latter, and that therefore the heat generated in them in the interior of the machine is rapidly conducted to cooler and more exposed parts, where it can be lost by radiation. In this way the connecting lugs to the commutator segments are useful for cooling purposes, and are sometimes so shaped as to drive cold air against the less exposed parts of the armature.

IV.—MAGNETIC CALCULATIONS

Further Notes on Design.—In the preceding pages the broad lines of good design for electro-magnets have been sufficiently dwelt upon (*see* pages 330 and 498, Vol. I.), and in applying these to the magnetic circuit of a dynamo it is only necessary to point out that it is very essential that they should be adhered to as closely as possible, and only departed from, however slightly, when some decided advantage, either mechanical, financial or otherwise, can be clearly obtained. Put shortly, the broad rules are that the magnetic circuit giving the required field in the gap should have a minimum reluctance, and should admit of the magnetising ampere-turns encircling it in such a way as to lead to a minimum expenditure of energy in maintaining the magnetising current. This means that the magnetic part of the circuit should be built of the best magnetic materials, that it should be as short as possible, and offer a large cross-section to the magnetic flux.

Materials.—In those parts of the magnetic circuit in which space is valuable, it is desirable to obtain high permeance in as small a compass as possible. In other parts, considerations of cost, both of materials and workmanship, may be allowed to influence the design and the material adopted. Thus, in the core of the armature of a continuous current dynamo, good Swedish charcoal wrought iron was, in the early days of dynamo development, used, as requiring the smallest amount of material for a given flux. If the design required small pole pieces they were also sometimes made of this material, which, however, had to be forged to shape, as it could not be cast.

For modern dynamo work the premier place is now held by mild cast steel, which (*see* Fig. 253, Vol. I.) at high-flux densities is more permeable than soft wrought iron. For manufacturing purposes it has all the further advan-

ages of a metal which can be cast to any desired shape, thus lessening the cost of production as compared with a metal which can only be worked by forging or tooling. It is also cheaper than cast iron, but is not so uniform in its magnetic properties. It is nearly pure iron, and should not contain more than from 0.2 to 0.25 per cent. of carbon, which reduces the permeability by diminishing the magnetic continuity. It also usually contains manganese (0.5 to 0.6 per cent.), and much smaller quantities of silicon, sulphur, and phosphorus. It is largely used for the cores of electro-magnets, where high permeability is a desideratum as reducing the cross-section and allowing the necessary ampere-turns to be obtained with a less expenditure of copper and energy. This material can also be produced in the form of rolled sheets, and is therefore used for the cores of armatures. Further numerical data relating to it will be found on page 51.

For heavy yokes and pole pieces, where lightness is not essential, but very often the reverse, good cast iron is used. Its permeability is increased by adding a small percentage, about 4 to 6 per cent., of aluminium. Another aluminium alloy of iron known as "mitis" metal is sometimes used; it is made by adding small quantities of aluminium to scrap wrought iron melted in a crucible. The wrought iron is thereby rendered fluid, and with rare sound castings can be obtained. Its permeability is about the same as that of ordinary good cast iron.

Shape.—The general considerations to be kept in view in designing the geometrical shape of the magnetic circuit have just been dealt with, and need not be further discussed here.

Excitation.—The chief problem presented by the magnetic circuit of a dynamo machine is the finding of the number of ampere-turns of excitation necessary to produce a given flux of magnetic lines across the gaps in which the conductors revolve between the pole pieces and armature. The E. M. F. set up in the armature of a bipolar dynamo is (see page 513, Vol. I.):

$$E = \frac{n Z N}{10^8}$$

Usually E and n are fixed by the conditions of the main problem, and therefore we have

$$Z N = \frac{E \times 10^8}{n}$$

Assuming that Z , the total number of active conductors, has also been fixed by other considerations, we have, finally

$$N = \frac{E \times 10^8}{n Z} \text{ maxwells.}^* \quad (1)$$

To take a concrete example, suppose that a bipolar dynamo is to give

* By the International Congress held in Paris in 1900 it was decided that the total number of lines of magnetic flux should be called so many "maxwells," in honour of Clerk Maxwell, who did so much to advance exact ideas concerning magnetic quantities.

70 amperes at 220 volts when running at 10 R. P. M. A reasonable figure for the armature resistance, with, say, 360 active conductors, is 0.132 ohm, and we then have

$$E = 220 + C_1 r_a = 220 + 70 \times 0.132 = 229.2 \text{ volts,}$$

$$n = \frac{600}{60} = 10 \text{ revolutions per second,}$$

$$Z = 360 \text{ active conductors ;}$$

whence

$$N = \frac{229.2 \times 10^8}{10 \times 360} = 6,370,000 \text{ maxwells,}$$

and the number of ampere-turns provided by the exciting circuits must be such that at full load this number of magnetic lines is driven across each gap between a pole piece and the armature.

Now the fundamental equation of a simple magnetic circuit is (see page 283, Vol. I):

$$N = \frac{M. M. F.}{\lambda} = \frac{4\pi a}{10^8} = \frac{I \cdot 26a}{\lambda} \quad (2)$$

where a = the number of ampere-turns (page 286, Vol. I).

When the circuit is of uniform cross section, as in the case of a continuous ring, we have

$$\lambda = \frac{l}{\mu} \quad (3)$$

and the calculation is an easy one. But in the case of a dynamo machine the calculation

is complicated by the fact that (i.) the various parts of the circuit are not uniform either in cross-section or in the magnetic quality of the materials, and (ii.) the magnetic circuit proper of the machine is plunged in a medium (air) the permeance of which is not so low as to be negligible, thus giving rise to serious "magnetic leakage," the existence of which cannot be left out of account (see Fig. 476, Vol. I).

For instance, in the simple case of a bipolar smooth-core under-type dynamo, given in outline in Fig. 34, the magnetic circuit consists of the following eight distinct and separate parts:—

- (1) The iron (A A) of the armature core.
- (2) The two air gaps between the armature core and the pole pieces.
- (3) The two pole pieces N and S.
- (4) The two cores (C C) on which the magnetising coils are wound.
- (5) The yoke Y connecting the cores at the ends of the armature.

In addition there are joints in various parts of the circuit.

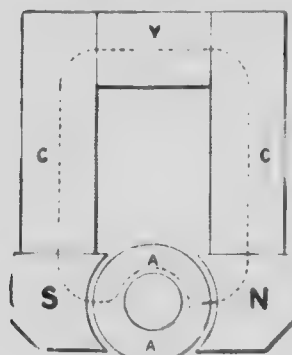


Fig. 34.—Magnetic Circuit of a Bipolar Dynamo.

Hopkinson's Method.—The method of calculating the magnetic field strength of a bipolar armature is based on the separate calculation of the ampere-turns in each part of the circuit. The flux through each of the different parts of the circuit is assumed to be the same. For this purpose we have from equations (2) the following equation:

$$N =$$

$$N = \frac{1.26 \cdot l}{\mu \cdot A} \quad (4)$$

In applying this formula to a bipolar armature it must be remembered that the value of μ depends on the magnetic field strength H ($= \frac{N}{l}$) of the magnetic circuit.

Since the connection between the two has to be

established, the magnetic field strength

must be known. This is done by

assuming a value for N and calculating the

value of l and A . It also be

or less indeterminate in certain

of the circuit and where the

an values adopted. In Fig. 35 a dotted line represents, except in

the case, a mean path of a magnetic line round the circuit. Shorter or

paths cannot be traced inside or outside this line, but a calculation

assumes that in the gaps, pole pieces, cores, and yoke the l 's may

be taken as the length of the line will be approximately correct. Similar remarks

apply to the value of the cross-sectional area (A).

Now the calculation in detail, for the various parts (1) to (5)

of the circuit specified above, it will be convenient to denote

the quantities in each part by attaching subscript corresponding

to the symbols used in equation (4). Thus we write for the

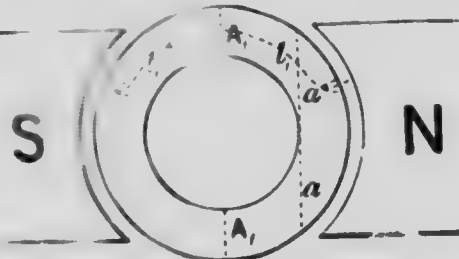


Fig. 35.—Bipolar Armature Calculations.

use a compromise must be made between the two values. In Fig. 35 a dotted line represents, except in the case, a mean path of a magnetic line round the circuit. Shorter or longer paths cannot be traced inside or outside this line, but a calculation assumes that in the gaps, pole pieces, cores, and yoke the l 's may be taken as the length of the line will be approximately correct. Similar remarks apply to the value of the cross-sectional area (A).

Now the calculation in detail, for the various parts (1) to (5) of the circuit specified above, it will be convenient to denote the quantities in each part by attaching subscript corresponding to the symbols used in equation (4). Thus we write for the

$$N = \frac{1.26 \cdot l_1}{\mu_1 \cdot A_1}$$

For approximate values of l_1 and A_1 we draw in the iron a line l_1 (Fig. 35) placed in what may be regarded as a kind of mean position between the lines which pass from pole tip to pole tip and the lines which take the path from the centre of one pole face to the centre of the other. The

length of this line within the iron may be taken for l_1 . For the area A_1 the total cross-section of the iron on the vertical diameter $A_1 A_1$ may be taken. For a rough calculation B may be taken as the value of $\frac{N}{A_1}$ at the cross-section, but for more careful work it must be remembered that B is less on the cross-section at $a a$. Having decided on the values of the quantities $l_1 A_1$ and μ_1 , the value of a_1 can be calculated for a sufficient number of different values of N up to the maximum to plot the curve A

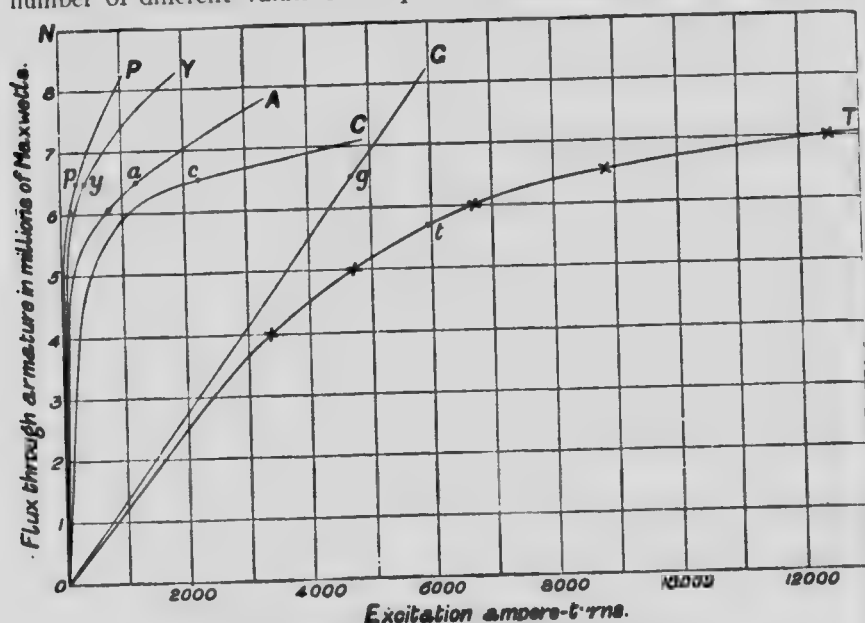


Fig. 36.—Predetermination of a Dynamo Magnetisation Curve.

(Fig. 36) for the armature. In this curve ampere-turns (a) are plotted horizontally, and the corresponding total armature flux N vertically.

The use of the magnetisation curves, Figs. 40 and 42, to obtain the ampere turns (a) required in any part of the circuit is simplified by remembering that the H of the curve corresponding to a given value of B is, from our present point of view, the "ampere-turns per centimetre" length measured in the direction of the flux. Having, therefore, read off the H required for the particular value of B under consideration, it is only necessary to multiply this value of H by the value of l in centimetres, and the product divided by 1.26 or multiplied by 0.795 ($\frac{1}{1.26}$) [see equation (4)] will give the a for that part of the circuit.

The calculation of a_2 for the air gap is simplified by the fact that μ_2

1 for all values of B . The length l_2 may be taken as twice the radial length* of the gap, since there are two gaps, one on either side. The area A_2 will be the cross-sectional area included within the polar angle and half-way between the surfaces plus an allowance for the spreading of the lines at the pole tips, technically known as "fringing." Since $\mu_2 = 1$, we note that a_2 varies directly as N , and we get a straight line G on the diagram for the connection between a_2 and N for the gap. The low slope of the line shows that we are here dealing with a part of the circuit which has a much greater effect on the total value of a than the core of the armature.

For the pole pieces a_3 can be calculated in the same way as a_1 for the armature. The length of the dotted line within the pole piece in Fig. 34 may be taken for l_3 , and a fair cross-section at right angles to this line may be taken for A_3 . Great accuracy is not necessary, for the resulting curve is so close to the vertical line as to show that the reluctance of the pole pieces does not have much effect on the ampere-turns required.

Allowance for Leakage.—In the cores $c c$ (Fig. 34) a new element has to be introduced into the calculation—namely, the effect of the magnetic leakage, to which attention was called in the historical section (see page 50, Vol. I.). Since the cores $c c$ carry the magnetising coils, the whole of the lines generated, both useful and useless, must pass through them. The value of N is therefore greater in the cores than it is in the armature, and allowance must be made for this increased value in calculating the corresponding value of B and the value of μ (or H) to use in equation (4). The ratio between the lines through the cores and the useful lines through the armature is usually known as the leakage factor, and is denoted by v . We have therefore the leakage factor

$$v = \frac{\text{lines passing through the magnet cores}}{\text{useful lines through armature.}}$$

A knowledge of v is usually arrived at theoretically by finding approximately the permeances† of the different leakage paths and adding them together, a process by which the total leakage permeance will be found. By comparing this with the permeance of the armature path the factor can be calculated. A practical method is to find the leakage factor by experiment on a machine of the type proposed to be built, and then by making an allowance for modifications assuming a value for the machine under consideration. A small error in the value adopted will not much affect the final result. In practice the value of v varies from about 1.10 to 2.00, but for many usual cases it lies between 1.30 and 1.40. The last-

* This is only correct when there is no current in the armature; under full load the field is distorted (see page 503, Vol. I.), and the value of l_2 for the gap space must be increased from 10 to 30 per cent. If the core be slotted, still further corrections must be introduced.

† Permeance is the reciprocal of reluctance.

named figure, 140, would mean that for every 140 lines set up on the cores only 100 passed usefully through the armature, the other forty being leakage lines. It is this excess which the designer aims at diminishing, and therefore the quantity ($v - 1$) becomes of importance. This quantity is smaller for large machines than for small machines of the same type, and less by 20 to 50 per cent. for toothed or tunnelled armatures than for smooth core. Slow-speed machines, being larger for their output than high-speed ones, have a less leakage factor than more quickly running machines of the same power.

Having settled on a probable value for v , and using Nv instead of N , the calculation for the cores $c c$ can be completed, and the curve c (Fig. 36) drawn on the same lines as before. The yoke y will be similarly treated in the curve y , regard being had to the lines which actually pass through it.

In this way the ampere-turns corresponding to various values of N (the armature flux) can be calculated for each part of the magnetic circuit. If the result is required for a particular armature flux of, say, N maxwells on open circuit, the figures can be simply added together as in the following table, which gives the details of a calculation by Dr. Silvanus P. Thompson for one point on the curve of a 21-kilowatt overtype dynamo:—*

Part of Magnetic Circuit.	Material.	Magnetic length (1)	Magnetic section (2)	Flux density (3)	$H \times 0.795$ (4)	Ampere-turns (1) $\times$ (4)
1. Armature core ...	Iron stampings ...	13.9	403	18,800	87	1,210
2. Two air gaps ...	Air, copper, &c. ...	2.22	1,610	4,570	3640	8,060
4. Two magnet cores ...	Wrought iron. ...	116.8	555	17,000	6.1	7,140
5. Yoke ...	" " ...	17.8	656	14,380	16.1	287
						16,697

The above are the details of the calculation for the flux necessary to give an E.M.F. of 115 volts at normal speed, and four or five similar calculations for other fluxes will enable the magnetisation curve at no load to be drawn. This is usually sufficient for practical purposes, but it is also possible to follow the method used by Dr. Hopkinson, by which curves are drawn connecting N and the ampere-turns for each part of the magnetic circuit, as in Fig. 36. In this diagram, as already explained, the ampere-turns required for excitation are plotted horizontally from left to right, and the corresponding values of the flux (N) through the armature are plotted vertically upwards in millions of maxwells. The curve $o a A$ gives the ampere-turns required to drive the useful flux through the armature, the bending over for high values of N being due to the magnetic properties of iron, already fully discussed. The straight line $o c$ gives the connections

* See "Dynamo Electric Machinery" (seventh edition), page 625.

between the quantities for the two air gaps. As these are non-magnetic, the permeability is constant ($= 1$) and the line is perfectly straight. The curves $o c c$, $o y y$, and $o p p$ are for the magnet cores, the yoke, and the pole pieces respectively. The curve $o c c$ bends over most rapidly because it is in the cores that the flux densities are pushed to their highest values. To obtain the total effect these curves must be added horizontally, and they will then give the curve $o t t$, which shows the excitation in ampere-turns for the whole magnetic circuit for different values of N , the armature flux.

Careful attention should be paid to the great influence of the reluctance of the gap spaces on the excitation required. This influence is shown both in the table and in the curves. For the particular flux for which the calculations in the former are made these gaps account for more than 48 per cent. of the required excitation, and the curves show a similar preponderating influence until the flux is approaching seven million maxwells. In this instance the gap spaces were only $\frac{1}{16}$ inch from iron to iron, and as the core was smooth the copper windings had to be packed into this space. The mechanical clearance was thus reduced to only $\frac{1}{32}$ inch.

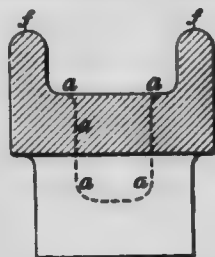


Fig. 37.—Cross-Section of Multipolar Circuit.

Multipolar Excitation.—The application of the above principles to the case of multipolar machines does not present any difficulty, and in some instances is even simpler than some of the examples met with in bipolar work. The general direction of the flux in a multipolar dynamo is shown in Figs. 37 to 39, prepared from data supplied by Messrs. Mather and Platt. Fig. 37 gives a cross-section of the iron between the poles and shows also the side view of the pole. There are projecting flanges $f f$ on either side, and the cross-section of the iron is substantially less between these flanges; moreover, at each projecting pole the iron is still further reduced by a hole as shown by the dotted line $a a a$. Figs. 38 and 39 give sections at right angles to the shaft through two adjacent poles, and including the flux-carrying part of the iron of the armature; the same reference letters are used as in Fig. 37. For simplicity straight-sided slots are shown. Fig. 38 is supposed to be a section through the central part of the field between the flanges, and on this section therefore the whole of the interpolar flux, as shown by the dotted lines, is confined to the lower part of the yoke ring. In Fig. 39 the section is near the side and through one of the flanges, into which, therefore, the yoke flux between the poles spreads. In the armature near the gap the flux is confined almost entirely to the projecting teeth, and very little of it passes through the slots until the teeth begin to get saturated.

With a clear idea of the general distribution of the flux, Dr. Hopkin-

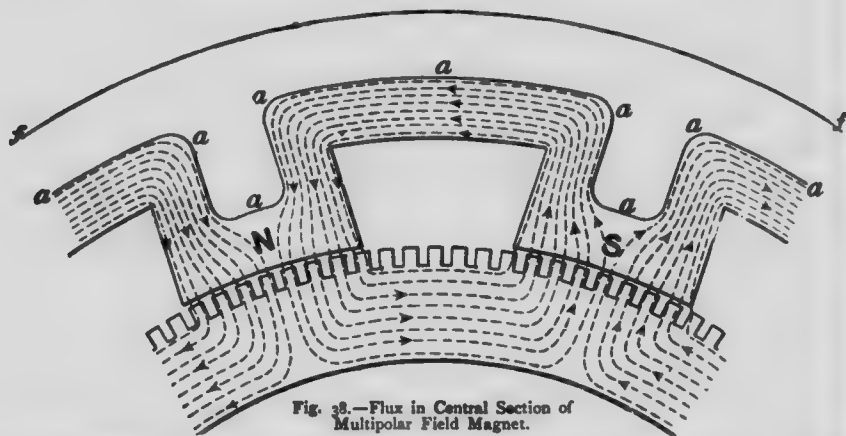


Fig. 38.—Flux in Central Section of Multipolar Field Magnet.

son's method for the calculation of the necessary excitation can be readily applied. Using the principles of the magnetic circuit and neglecting leakage, we obtain, for a first approximation, the following general equations:—

$$2M = \frac{N}{2}(\lambda_1 + \lambda_4) + N \times 2(\lambda_2 + \lambda_3) \quad (1)$$

$$\text{or} \quad N = \frac{4M}{\lambda_1 + \lambda_4 + 4(\lambda_2 + \lambda_3)} \quad (2)$$

where M = magnetomotive force of each magnetising coil.

N = total flux in maxwells from each pole.

λ_1 = reluctance of armature between two poles.

λ_2 = reluctance of each air gap.

λ_3 = reluctance of one magnetic core (including pole piece).

λ_4 = reluctance of yoke between poles.

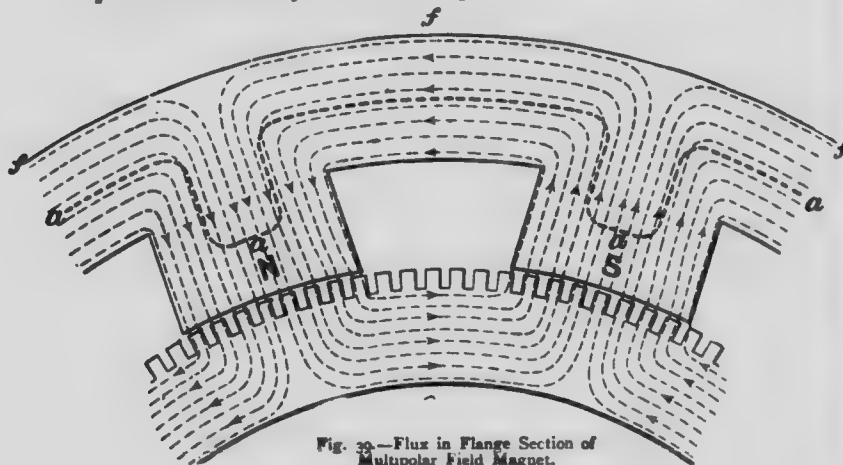


Fig. 39.—Flux in Flange Section of Multipolar Field Magnet.

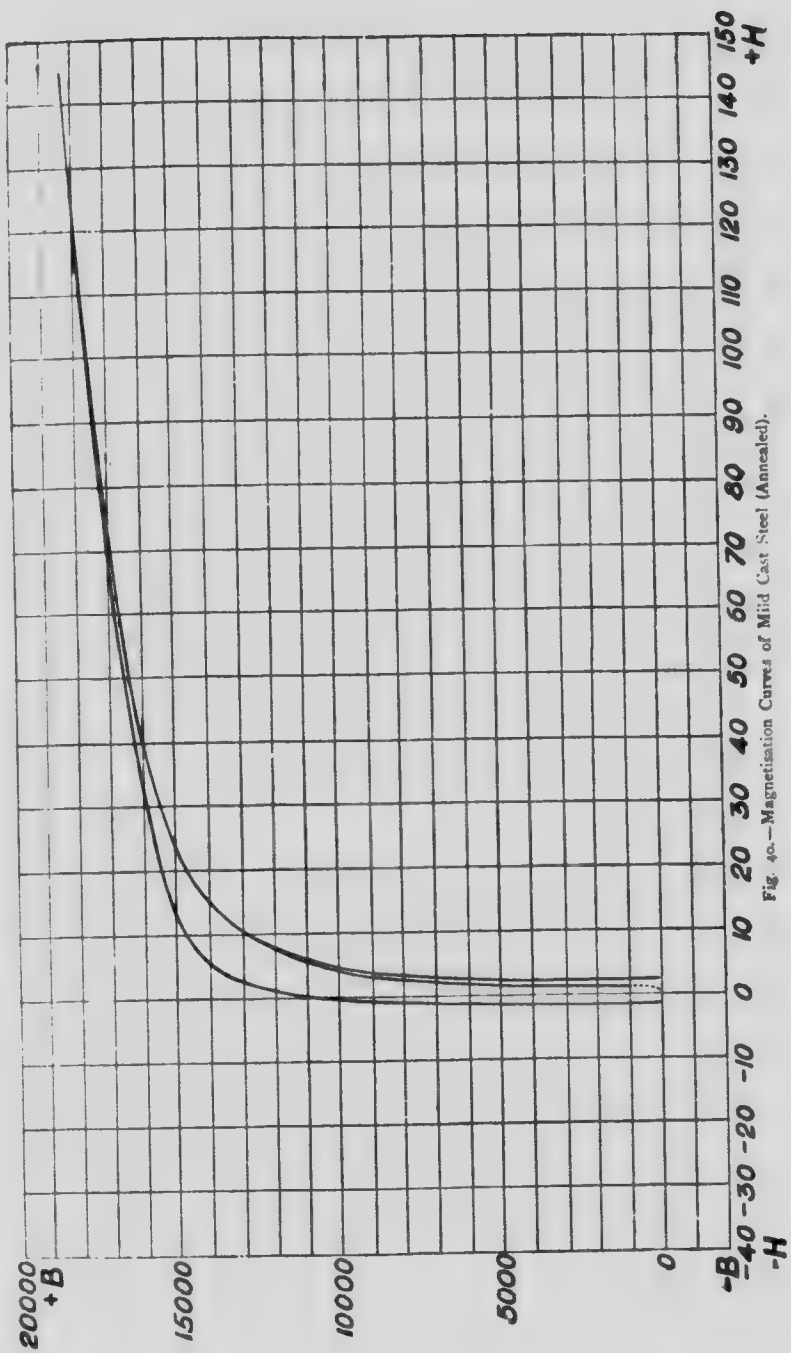


Fig. 40.—Magnetisation Curves of Mild Cast Steel (Annealed).

Besides allowing for the leakage factor in the usual way it is obvious, from Figs. 38 and 39, that part of the yoke behind the core must be included in λ_3 , and that the teeth and some of the iron of the armature under the pole faces must be treated differently from the iron not under the poles: The application, however, will present but little difficulty to the reader who has mastered the preceding case of the bipolar machine.

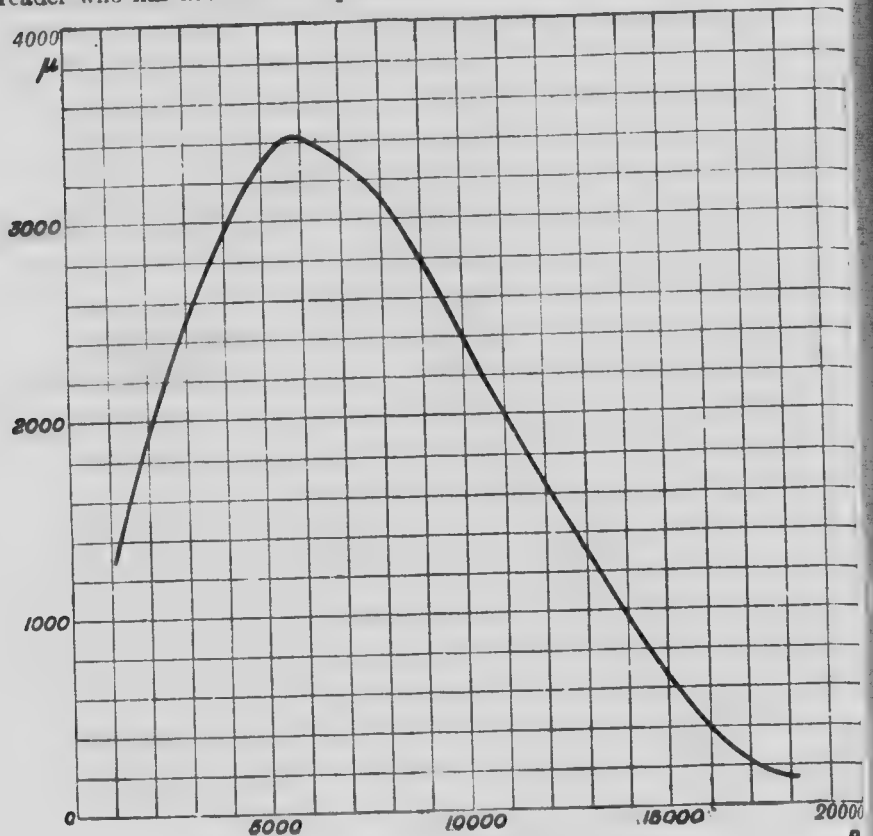


Fig. 41.—Permeability Curve of Mild Cast Steel (Annealed).

Use of Magnetisation Curves.—In calculating curves similar to those in Fig. 36, the magnetisation and permeability curves of the actual material to be used in construction should be obtained. Some such curves were given in the first volume of this book in Figs. 252 and 253. Since these curves were taken mild steel has come into such wide use for dynamo field magnets that manufacturers have paid special attention to the details of its manufacture in order that the product may be magnetically and

mechanically of the best. In Fig. 40 we give the magnetisation curves and in Fig. 41 the permeability curve of a sample of annealed mild cast steel made by Otto Gruson and Co., of Magdeburg. In Fig. 40 the $+$ value of H has been taken from 0 to 145, and then diminished and reversed in the usual way. To show the hysteresis loop — values of B have been plotted as $+$, with the corresponding — values of H also as $+$. The right-hand curve has been plotted in this way, and with the left-hand curve encloses one-half of the hysteresis loop, the total area of which corresponds to a dissipation of 13,600 ergs of energy per cycle per cubic centimetre of material. The remanence for the particular maximum magnetisation employed is 10,200 gauss, and the retentivity 1.5. The curve rises to higher values than the "soft annealed iron" curve in Fig. 252, and at $H = 50$ B is 16,500. The figures from which these curves are plotted are given in the annexed table. The permeability curve of Fig. 41 should be carefully compared with the permeability curves of Fig. 252, Vol. I.

EXPERIMENTS IN PERMEABILITY OF MILD STEEL

H	B	μ	H	B	H	B
+ 0.0	+ 1,130	1,240	+ 145.3	+ 18,250	- 1.75	- 3,420
1.2	2,610	2,200	117.9	17,830	2.2	6,240
1.35	3,740	2,790	82.8	17,220	2.7	7,680
1.55	5,200	3,310	62.7	16,800	3.7	9,240
2.15	7,040	3,260	47.7	16,410	5.9	11,000
2.7	8,160	3,010	34.7	16,000	8.5	12,410
3.75	9,480	2,540	24.2	15,590	11.9	13,460
5.05	11,160	1,880	17.8	15,270	18.0	14,510
8.55	12,440	1,460	11.8	14,810	24.3	15,110
12.0	13,970	1,120	7.15	14,220	34.2	15,710
18.1	14,510	800	3.2	13,080	46.6	16,220
24.6	15,120	610	0.8	11,320	61.6	16,680
34.5	15,710	460	0.35	10,560	82.2	17,160
46.8	16,230	350	0.7	8,590	117.5	17,810
62.3	16,680	270	1.0	7,310	145.3	18,250
82.7	17,150	210	1.25	6,110		
118.4	17,810	150	1.45	2,290		
145.3	18,250	130	1.55	620		

The table on page 48 sets out a convenient way of calculating the no-load excitation. On inspection, it will be noticed that the most convenient form in which to prepare the magnetisation curves for practical use is not to plot B against H , but to plot B against $H \times 0.795$. For a given value of B it will then be possible to read off at once without further calculation the ampere-turns necessary to drive the flux at that density through each centimetre length of the material through which it is to be driven. Thus the figures in column (4) will be read off at once from the curve when the figures in column (3) have been calculated. Column (5) can then be quickly calculated by multiplying together the corresponding figures in

columns (1) and (4). The change only necessitates altering the scale of the abscissæ or horizontal ordinates.

To emphasise this point, Fig. 42 gives the magnetisation curves for two samples of magnetic iron produced by Messrs. Joseph Sankey and Sons, Ltd., of Bilston, Staffordshire. In these curves the abscissæ are

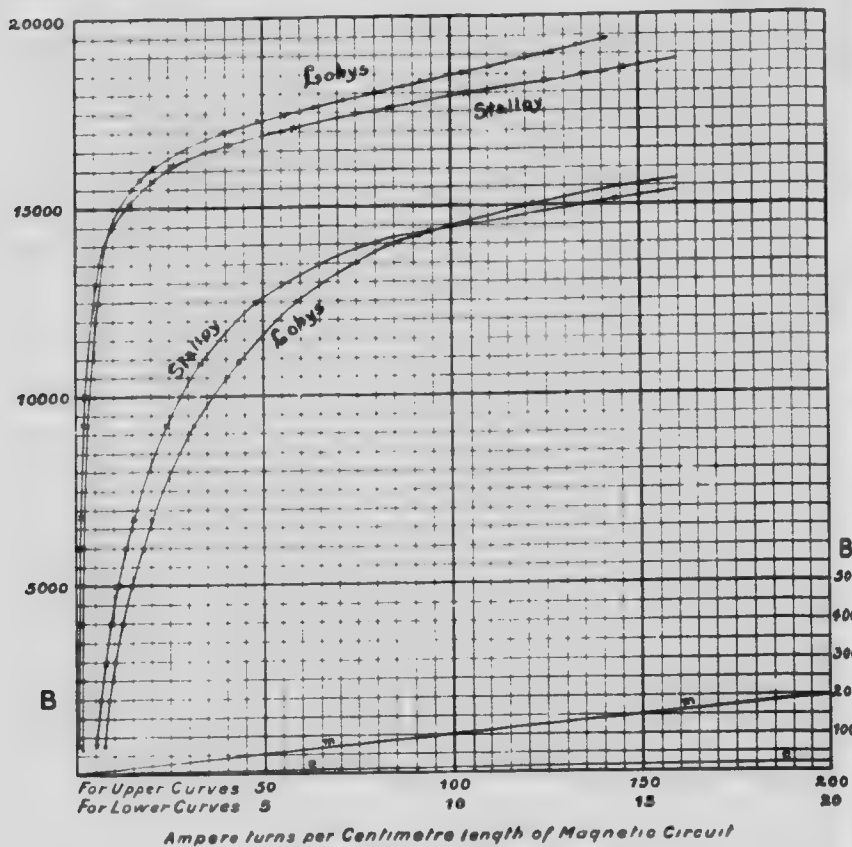


Fig. 42.—Magnetisation Curves of Special Magnetic Irons.

"ampere-turns per centimetre length," measured along the lines of magnetic flux. To obtain the values of H , the numbers plotted would have to be multiplied by 1.257.* The curve marked "Lohys" has reference to a fine, soft sheet-iron sold under this name, whilst that marked "Stalloy" is manufactured under the patents of Messrs. Hadfield, of Sheffield, and is

* If the curves are required in British (inch) units the vertical ordinates (B) must be multiplied by 6.45 and the abscissæ by 2.54. It will be a useful exercise to re-draw the curves to these scales.

probably a mild low-carbon steel. The exact method of manufacture is jealously guarded as a trade secret, but its good magnetic properties are probably largely due to the heat and mechanical treatment of the material, as well as to its chemical composition, which can, of course, be readily ascertained by well-known chemical methods of analysis. To exhibit more clearly the magnetic properties at low-flux densities, the lower parts of the curves are also shown, plotted to a more open scale of abscissæ.

Air-Gap Reluctance.—Attention has already been drawn, in connection with the detailed calculation tabulated on page 48, to the large proportion which the excitation necessary to force the flux across the air gaps bears to the total excitation of the machine. The example given was taken from a somewhat old type of bipolar machine, in which this proportion is much below that which it attains in most modern machines, and moreover, the calculation had reference to a point high up on the magnetisation curve, where the air-gap reluctance is relatively less important. Without giving all the details, the following are results taken from another example, this time of a modern six-pole machine, and for a point corresponding to about the full voltage on open circuit. The figures given are for one pair of poles :

	Ampere-turns				
1a. Armature core..	..	..	..	..	16·1
1b. Two teeth ..	..	..	..	..	29·5
2. Two air gaps ..	..	..	..	..	4,675
4. Two magnet cores ..	..	..	..	..	352
5. Yoke ..	..	..	..	..	234·4
					5,307

In this example it will be noticed that the air gaps' excitation instead of being only 48 per cent. of the total excitation is as much as 88 per cent., from which it is obvious that in the general design the dimensions assigned to the air gaps must be very carefully considered.

Another method of contrasting the numerical difference between the non-magnetic and the magnetic materials of the circuit is given in Fig. 42, in which are drawn low down in the diagram two sloping lines *cc* and *mm*. The lower of these *cc* represents to the same scales as the uppermost curves the flux in the air gap which would be given by the excitations plotted. The upper line shows either (i.) the air-gap flux as shown by a more open vertical scale on the right-hand side, corresponding to the ampere turns per cm. (0-200) scale or (ii.) the flux measured on the left-hand scale, which would be produced if the horizontal scale (0-200) represented ampere turns per millimetre length. In either case, the contrast is very striking between the flux produced by a given excitation in magnetic and in non-magnetic materials.

With these striking statistical differences, it will be readily understood that the removal of iron from the slots of a slotted armature core to make room for the windings, must seriously affect the reluctance of the magnetic circuit, as it must materially increase the reluctance of the air-gap sections which are now seen to be the most important in the whole circuit.

It is not, however, so easy to see how an exact calculation can be made of the extra excitation required on account of the slots. In fact, such an exact calculation is very complicated, and the full consideration of the problem would carry us far beyond our limits in minute details without introducing anything essentially new in the broad principles involved. A simple method is to assume that all the flux passes down the teeth and none at all through the slots; but this is evidently an over-correction, especially as this crowding of the flux into the teeth must materially increase the flux density in them and lower their permeability (see Fig. 30), thus increasing the relative importance of the alternative path through the slots.

It will be noticed that in the example on page 55, the excitation for two teeth has been given separately from that for the armature core, and also that this excitation is nearly double that required for the armature core itself.

Various mathematical rules have been formulated for a nearer approximation, for which the reader who is interested should consult books on dynamo design. We shall only here refer to a very striking experimental method of handling the problem devised by Professor H. S. Hele-Shaw. The method depends on the mathematical analogy between the steady flow of an incompressible fluid such as water through a circuit in which there are varying frictional retardations, and the magnetic flux in a circuit of varying permeance per unit length. He caused differently coloured streams of water to flow side by side between two parallel glass plates somewhat close together. Between these plates he introduced obstructions shaped to scale like the air gap and the slots of a dynamo, and in designing these obstructions, he aimed at increasing the resistance to the flow of the water in numerically the same ratio as the air gap increases the reluctance of the magnetic circuit. By projecting the flowing bands of water on a screen, he produced a visual picture of the magnetic flux, by examining which, it was possible to determine the "correction-coefficient" to be applied in the magnetic calculation.

Two of Professor Hele-Shaw's diagrams are reproduced in Figs. 43 and 44, which are taken from a paper read before the Institution of Electrical Engineers in 1904. The bands of water, alternately bright and dark, are flowing vertically downwards, and would appear as parallel straight lines if no obstructions were placed in their paths. Rectangular obstructions, however, representing the air gap (horizontal) and a slot (vertical) are inserted, with the result that the latter forces the vertical bands outwards, and they are crowded into the spaces which represent

the teeth. Each diagram has a complete slot in the centre, the spaces on either side of which represent one-half of each adjacent tooth. The whole diagram therefore represents the flux from the centre of one tooth to the centre of the next. It will be noticed that quite a number of the bands penetrate into the slot, more especially in Fig. 44, and it will be evident



Fig. 43.



Fig. 44.

Prof. Hele-Shaw's Water-Flow Diagrams, showing the Paths of Lines of Magnetic Flux in Tooth and Slot.

that it is a question of the relative dimensions of gap, slot and tooth. In fact, both mathematically and experimentally it is found that the ratios which determine the lines of flow are $\frac{s}{t}$ and $\frac{s}{g}$ where:—

s = width of slot

t = width of tooth

g = length of air gap measured vertically.

By inspection of the diagram the ratio of the number of stream lines

per unit length well under cover of a tooth to the mean number of stream lines per unit length for tooth and slot can be determined. This ratio is the correction coefficient by which the gap length must be multiplied to obtain the length to be used in the calculations explained above.

Size of Magnetising Conductors.—The number of turns required for each bobbin or coil of the circuit having been ascertained, it is next necessary to calculate the cross-section and length or weight of the conductor to be used. In the designing of the magnetic circuit the length and size of the core of each coil will probably have been fixed, and these will determine the dimensions of the bobbins, with the one exception of the depth of the windings.

Before proceeding farther, however, it is desirable to fix the rise of temperature of the coils which may be permitted when the machine is run for a long period with full current in the conductors. The greater part of the heat, though not all, will be radiated from the outer surface of the coils, and the maximum and steady temperature will be attained when the rate of loss exactly balances the rate at which heat is being produced by the passage of the current through the conductors. Experiment shows that with the surface in the usual state in which it is on a well-kept dynamo the radiation may safely be assumed to be not less than $\frac{1}{100}$ watt per square inch for each degree Fahrenheit that the temperature of the radiating surface is above the temperature of the surrounding atmosphere. It will be observed that in this way of putting it the *rate of loss of heat* is measured in *watts*, which is perfectly correct, for the watt is a unit of power, and therefore may measure the rate at which energy is being transferred from one point to another.

If now we assume that the whole of the heat is radiated from the outside surfaces of the coils we shall be on the safe side, for we know that some of it escapes in other directions. Making this assumption, let us further assume that

v = the P. D. of the exciting coil.

c = the current in the exciting coil.

s = the required number of turns.

θ = the permissible maximum rise of temperature in degrees Fahr.

P = the outside perimeter of the coil in inches.

l = the length of the coil in inches.

d = the depth of the windings in inches.

x = the gauge of the wire (supposed square) in inches.

Then we have—

Power expended in the coil = vc watts.

Power radiated from surface of coil = surface $\times$ excess temperature $\times \frac{1}{100}$
 $= Pl \times \theta \times \frac{1}{100}$ watts.

Therefore, on the assumption above referred to, we have

$$V C = \frac{P l \theta}{100} \quad (i.)$$

Again, the

$$\text{number of turns per layer} = \frac{l}{x}$$

$$\text{number of layers} = \frac{d}{x}$$

$$\text{and therefore the total number of turns, } s = \frac{l d}{x^2} \quad (ii.)$$

From (i.) and (ii.) by multiplication

$$V C s = \frac{P d \theta l^2}{100 x^2} \quad (iii.)$$

or

$$x = \frac{l}{10} \sqrt{\frac{P d \theta}{V C s}} \quad (iv.)$$

If all the quantities on the right-hand side are known, it can be numbered that the product $C s$ is the ampere-turns, then x , the gauge of wire, can be calculated. The wire, for simplicity, has been assumed to be square, but if it be rectangular or circular in section the necessary corrections can easily be applied. The calculation can now be readily carried farther, and the actual length and weight of wire, as well as its resistance, can be ascertained, due allowance being made for the requisite thickness of insulation, which must also be allowed for in taking the dimensions already referred to.

The above gives the calculation for a shunt coil. For a series coil the current and the ampere-turns being given, the actual number of turns is known, and all that is required is to calculate the length of the coil, which will give the necessary radiating surface for an assumed gauge of wire or depth of winding.

V.—THE INDUCTIVE CIRCUIT: THE ARMATURE

The three chief methods of winding the electric conductors in modern machines are the ring, the drum, and the open coil. Of these the second is now the most widely used and will be first dealt with very fully. Relatively to the iron of the core the wires may be entirely outside the iron, as in smooth-core machines; or they may be in slots, as in the old Pacinotti motor (page 538, Vol. I.); or they may be entirely "buried" in the iron, lying in holes within its mass.

Before, however, discussing the method of winding, a few words may profitably be devoted to the materials, both conducting and insulating, which are employed, and also to the preliminary calculations which fix or tend to fix the size and number of conductors required.

Materials.—For the *conductors* we should like to use material of the

very highest conductivity procurable, because the space occupied by them is extremely valuable. The E. M. F. set up in a conductor sweeping across a magnetic field depends on its velocity, its length, and the intensity of the field. The resistance of the conductor does not, therefore, affect the E. M. F. But when the machine is working these conductors must carry currents and will become heated, because they have resistance. In order that the heat produced, and therefore the temperature rise, may not be excessive, a sufficient cross-section, depending directly on the specific resistance of the material used, must be provided. Hence it is that material of the highest conductivity should be selected. By reference to Table IV. (see page 751, Vol. I.) it will be found that silver has the highest conductivity of all known materials, but that the conductivity of copper is only

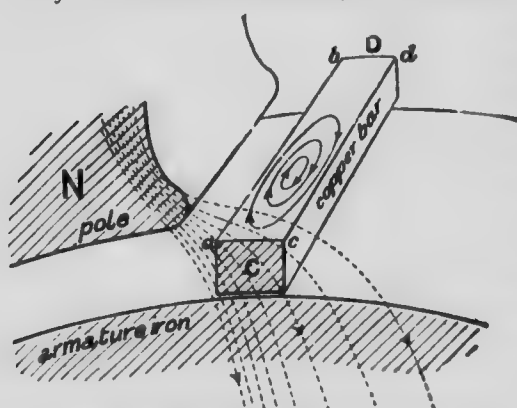


Fig. 45.—Eddy Currents in Solid Armature Conductors.

therefore, universally used for the material of the conductor.

As regards the *shape of the conductors*, since space is valuable it is obvious that square or rectangular sections will be more economical on smooth-core armatures than round wires. In slots this is also usually the case, though not necessarily, as the slot can be shaped to fit the wire if there be only one wire per slot. In tunnelled cores the holes are usually round or oval, and the conductors fit them.

The actual *size of the cross-section* is determined by the current density permissible and the current to be carried at full load. In well-ventilated armatures the current density may be as high as 2,000 amperes or more per square inch. In making the calculation the designer must bear in mind that no armature conductor has to carry the full current of the machine, and that in multipolar machines the current per conductor may be considerably less than the full load current in the outer circuit. The actual current carried depends on the number of poles and the winding, and can be readily found when these are known.

about 4 per cent. lower. Theoretically, therefore, if cost were no object, we should wind our armatures with silver wire. But cost cannot be ignored where so great a quantity of material is required, and even with silver so low as two shillings an ounce it cannot commercially compete with copper, which is nearly as good a conductor, and at £80 per ton only costs a little over 0.5d. per ounce. Copper is,

Eddy Currents in the Conductors.—In smooth-core and narrow-toothed armatures for heavy currents the copper should be laminated, because of the tendency to generate eddy currents in it, if solid, as it passes through any rapidly varying part of the field. Thus, in Fig. 45, let cd represent part of a solid conductor just passing from under the tip of the pole piece N of the field magnet, the section at c being near the end of the length; the few lines of force drawn are supposed all to lie in the plane of this section. It is obvious that the edge cd of the copper bar is in a much weaker field than the edge ab , and that therefore, since the velocities are equal, the E. M. F. along cd will be less than the E. M. F. along ab . This will give rise to swirls of current in the substance of the copper as shown (compare Fig. 588, Vol. I.); such eddy currents will absorb energy which will be dissipated in heating the conductor unnecessarily, and thus raise the temperature and lower the efficiency of the machine.

The necessity for guarding against these currents, sometimes referred to as parasitic currents, has almost ceased to exist in modern machines, because of the very general adoption of toothed armatures, in which the conductors are well surrounded by iron, whose presence tends to destroy the above inequality of field. As cases, however, still arise where the slots are deep and fairly open at the top, and as the subject is a very interesting practical application of scientific principles, it is worthy of at least brief consideration.

In seeking a remedy for the trouble it must be remembered that the eddy currents are due to very small differences of E. M. F., and that they are large only because of the excessively low resistance of their circuits. By properly laminating the conductor so as to remove the latter cause they can be practically abolished. One method is to form the conductor of stranded wires with a short "lay" soldered together only at the ends; in passing across the core any individual strand crosses the whole conductor from front to back, and vice versa, more than once, and therefore has only an average E. M. F. generated in it. It is found that the layer of dirt or oxide on the outside of an ordinary uncleaned copper wire has quite sufficient resistance to prevent the eddy currents passing between a strand and its immediate neighbours, and therefore these currents cannot be set up. These stranded wires can be squeezed by hydraulic or other pressure into a square or rectangular section without impairing the efficiency of the laminations.

In the days of smooth-core armatures Crompton and Swinburne built up large armature bars of two vertically laminated strips, one of which passed under the other at the middle of the length. Thus one strip was for half its length on the ab edge (Fig. 45), and for the other half on the cd edge of the bar, whilst its companion, also crossing over in the middle,

occupied the other halves. On the whole, therefore, each strip had the same E. M. F. set up in it, and, as by reason of dirt or light insulation, currents could not pass from one strip to the other, the eddies were killed. One disadvantage of this method was that it necessitated the machining out of a part of the middle of the armature core to make room for the cross-over. Other methods of twisting in the centre of the length, and free from this disadvantage, were devised.

In regard to *insulators* the choice of materials is more varied than for conductors. Two results have to be secured: the copper conductors must be insulated from one another and also from the iron of the core. The material selected should be able to stand heating without losing its insulating properties, and should be fairly flexible. Besides being a good insulator, it should have great dielectric strength; in other words, it should not be easily pierced when subjected suddenly to a great electrostatic strain caused by a rapid rise of potential in one of the conductors it is protecting. *Mica* is an excellent insulator, has a very high dielectric strength, and is unaffected by heat, but it is lacking in flexibility. Various preparations of mica, known as *micanite*, *mica cloth*, etc., have been invented, which, whilst retaining to a great extent the high insulation of mica and its high dielectric strength, are more or less flexible. *Cotton* or *linen* cloth, or *muslin*, or *paper well oiled* with pure linseed oil, and from which the moisture has been expelled by heating, give excellent results; many preparations of these and combinations with various cements and gums have been brought forward from time to time and have been widely used. *Rubber*, *rubber tape*, *silk*, or *asbestos* are used in certain cases.

The actual thickness of insulation depends upon the working voltage of the machine, and the mechanical and electrical strains to which it may be subjected. The conductors are usually covered, before being put in position, with single or double cotton, or silk, and well oiled or varnished with a flexible varnish. In built-up coils they are further served with insulating tape, and specially protected at all angles and bends. In smooth-core armatures the core is coated with japan or enamel, and then covered with one or more of the above-named flexible insulators, the thickness of insulation varying from 20 to 200 mils. On edges and ends the thickness is increased. In toothed or tunnelled armatures the iron channels are lined with troughs or tubes of micanite, mica cloth, *presspahn*, or similar material, from 10 to 100 mils in thickness. The insulated conductors are then laid in these troughs or tubes. When completed, and sometimes before completion, the armature is well baked in an electrically controlled oven, where the temperature is kept at about 68° C., or, if the insulating material will stand it without deterioration, at somewhat above 100° C. By prolonged baking all moisture is expelled, and the insulation improved.

Calculation of Windings.—The fundamental equation for determining the windings (see page 513, Vol. I.) for closed coil bipolar machines is

$$n z N = E \times 10^8 \quad (1)$$

for multipolar machines, if p be the number of pairs of poles, the formula becomes

$$k p n z N = E \times 10^8 \quad (2)$$

where N is now the flux per pole whatever be the number of poles, and k is a constant depending on the scheme of winding. If the various sections are all parallel, which is the most common case, $k p = 1$, and equation (2) becomes the same as equation (1) for this case. For other methods of winding $k p$ has a higher value, these methods being generally employed to increase the voltage of the armature for a given speed and output.

Since there are three principal unknown quantities, n , z and N , there is a certain amount of choice, and previous experience must be relied upon for a start. The value of n , which often depends on controlling and outside considerations, is first fixed. When n is known an approximate diameter of the armature can be fixed by the consideration that, except for large machines, the circumferential velocity should not exceed 3,000 feet per minute; about 2,000 feet per minute is a good working figure. Knowing the diameter of the armature and the cross-section of the conductors, allowance being made for insulation thickness, a value can be assumed for z or z and p combined, and then the corresponding value of N found from equation (1) or (2). When from this the necessary polar dimensions are worked out from considerations of flux density, etc., the resulting proportions may not be good, and the previous assumptions may have to be revised, but it will not be difficult to hit upon satisfactory figures ultimately and rapidly.

Number of Commutator Segments.—Having obtained an apparently suitable value for z , the number of external conductors on the armature, the next point is to determine the number of sections on the commutator. The maximum possible number is equal to z for ring armatures, and to half of z for drum armatures. But a many-part commutator is expensive, and subdivisions of these numbers may be taken, provided the P. D. between adjacent segments does not rise so high as to maintain an arc with the current that is being carried across the thickness of the insulation (usually about 40 mils) should this be ruptured. Another consideration which tends to fix a minimum value to the number of bars is the fluctuation of the voltage caused by the act of commutation (see page 488, Vol. I.). This ceases to be appreciable when there are not less than 32 or 35 bars per pair of poles. The lower limit may be still further raised by difficulties of commutation, to which we shall refer more fully when dealing with armature reactions. If the values of z and p , or of z alone, clash with these conditions, fresh assumptions must be made and more suitable values obtained.

Winding Schemes.—(a) *Bipolar Machines.* It is, of course, of supreme importance that the various active conductors in the armature should be properly connected together, so that when the brushes are correctly adjusted the various induced E. M. F.'s should be all in the same direction in the circuit. We have already (see page 510, Vol. I.) pointed out the evils due to the inductive pressures being wrongly directed because of bad design; the point now being considered is how best to guard against carelessness in connecting the various conductors together. For this purpose it is necessary to issue carefully drafted instructions to the workmen to whom the task

of making the connections is entrusted.

In *ring* armatures the instructions are simple, since it is only necessary to connect the end of one turn to the beginning of the next, and to connect to the commutator bars successively at the end of each section, which may consist of one or more complete turns.

In *drum* armatures matters are more complicated, as will readily be perceived on inspecting Fig. 46, in which 48 conductors in a single layer are to be con-

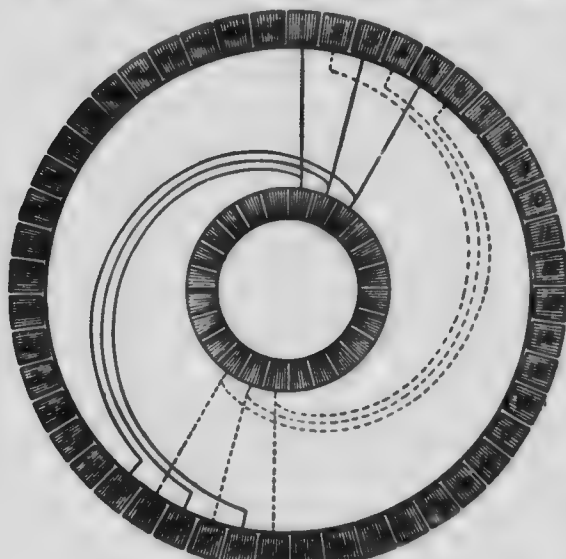


Fig. 46.—Diametral Drum Winding.

nected to form a drum winding with a 24-part commutator attached; in other words, each complete turn is to be connected to the commutator. It might be supposed that all that is necessary is to connect at the front No. 1 to No. 25, which is diametrically opposite, and the back end of No. 25 to No. 2, whose front end should be joined to No. 26, and so on, a bar of the commutator being tapped as each front connection goes across. It will, however, soon be found that this will not work, for when Nos. 1 to 12 have been thus joined to Nos. 25 to 36 twelve consecutive bars (i.e. one-half) of the commutator will have been joined to the conductors in two opposite quadrants only, and the brushes 180° apart on the commutator would only be 90° apart on the armature. It is obvious that this is electrically wrong. Moreover, mechanical difficulties would be encountered. To set matters right the *intervals* for connection should

No. 25 instead of 24 at the front end, and 23 at the back. Thus, at the front No. 1 should be joined to No. 26 ($1 + 25$), and at the back No. 26 to No. 3 ($26 - 23$); for the next turn No. 3 at the front to No. 28 ($3 + 25$), and No. 28 at the back to No. 5 ($28 - 23$), and so on. In this way every wire is missed, and by the time twelve turns are completed and No. 1 to the commutator the odd wires from 1 to 23 and the even wires from 26 to 48 will be joined up, and a fresh start can be made for the last five turns by joining 48 to 25 ($48 - 23$) at the back. The student is advised to work this example through carefully in detail.

The directions to the workman can be embodied in a winding table as follows:—

B	F	B	F	B	F	B	F	B
U	D	U	D	U	D	U	D	U
1	26	3	24	5	30	7	32	
9	34	11	36	13	38	15	40	
17	42	19	44	21	46	23	48	
25	2	27	4	29	6	31	8	
33	10	35	12	37	14	39	16	
41	18	43	20	45	22	47	24	

In this table the letters B and F mean *back* and *front*, and the letters U and D mean *up* and *down*. Thus, we are told that passing *up* No. 1 from the back we are to join it across the front to No. 26, which passing *down* we join to No. 3 at the back, whence we come *up* No. 3 to the front, where we join it to No. 28, and so on. A glance at the table will show that when a proper start has been made the numbers follow general laws, and can be written down almost automatically. For numbers that would exceed 48 this number must be subtracted. The table contains all the conductors, and no one twice over.

The above is an example of what is known as *diametral* winding. Other windings, devised to secure sparkless running or regulation, will be referred to later.

(b) *Multipolar Windings*.—A little consideration will show that in multipolar machines, whilst avoiding the difficulties above alluded to, a greater freedom of choice is possible. Thus, when in the course of the winding a conductor opposite one pole has to be joined to a conductor in a particular position opposite the adjacent pole, a choice of conductors can be made from the pole in front or the pole behind. This choice has given rise to two general methods of scheming out the connections, one known as *lap winding* and the other as *wave winding*. In the first the windings eventually form a series of coils overlapping one another, as in Fig. 47, whilst in the wave winding the connections are continually going forward, as in Fig. 48. In both figures the groups of vertical lines represent con-

ductors in nearly similar polar positions, and the sloping lines represent the connections. The barbed arrow-heads on the thick vertical lines represent the directions in which the F. M. F.'s are set up as the conductors are moved over the pole faces from left to right. If the circuits indicated in the connections are traced out it

will be found that these E. M. F.'s are connected in *series*, the E. M. F.'s in the conductors passing a south pole being then added to those in the conductor passing a north pole. The direction of motion of the conductors is shown by the light horizontal arrows.

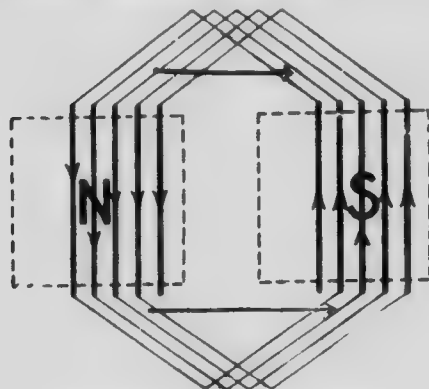


Fig. 47.—Connections for Lap Winding.

cases the diagrams may be regarded as diagrams of *bar windings*. If each conductor completely fills a slot, then a study of Fig. 46 will make it evident that in Fig. 47 the bars shown must lie in every other slot. Another way of putting it is that if we regard the bars shown on pole S as *leading* bars, and those shown on N as *following* bars, in each complete

(c) *Bar windings*.—In Figs. 47 and 48 the thick lines representing the conductors may each be regarded as a single conductor completely filling or half-filling a slot in a slotted armature or occupying a similar position on a smooth-core armature. In either of these

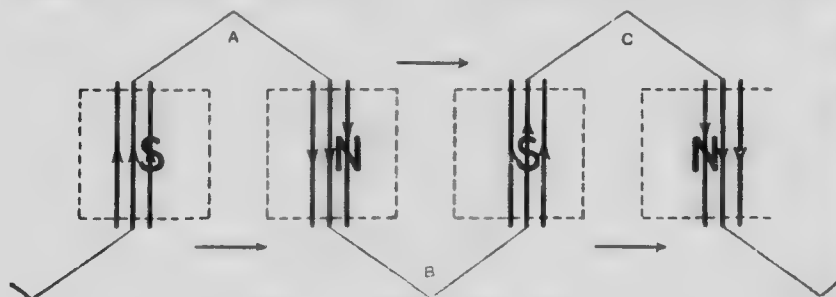


Fig. 48.—Connections for Wave Winding.

turn when the winding is completed leading and following bars will lie alternately round the whole periphery of the armature. Still another way of looking at the problem is to regard the bars which we have just referred to as leading and following bars as respectively the *odd* and *even* numbered bars of Fig. 46. If, however, there are two bars per slot or two layers on a smooth-core winding, then the necessary conditions will be fulfilled by

the leading (or odd-numbered) bars the *top* bars and the following (even-numbered) bars the *bottom* bars, and in Figs. 47 and 48 the thin lines will represent the positions of successive slots or successive peripheral positions on a smooth core.

Coil windings.—In actual practice, however, such methods of placing one or two conductors per slot or peripheral position may not develop the necessary E. M. F. or find room for the whole of the conductors z which the calculations based on the equations on page 63 show to be necessary. For such cases the thick lines of Figs. 47 and 48 may be regarded as representing two or more conductors in a *coil* with the necessary number of connectors at both top and bottom in each figure to complete the winding. Illustrations of such coils (see Figs. 58, 65 and others) will be given presently, and also of the methods in which they are assembled on the armature. A reference back to Fig. 47 or Fig. 48 will then enable the reader to follow most of the cases illustrated. Perhaps the chief difficulty which will occur will be as to how such coil windings are joined up to form a wave winding. This difficulty will disappear if it be remembered that the successive *coils* of such a winding will occupy the position A and c in Fig. 48, and that the intermediate position B will be filled as the wave, so to speak, travels successively round the periphery. Though at the stage illustrated there will be many connectors back and front at the positions A and c, there will only be a single connector, as shown at the front from A to c across the space B. By a little modification the same idea leads quite simply to a mixed lap and wave winding.

The windings now being described are all *closed coil* or *re-entrant* windings; that is, the winding always returns into itself to form a closed coil, as explained in Vol. I. Open-coil windings, which are now very little used, are distinct, and must be separately treated for each case. In re-entrant windings there are still further developments for special purposes, some of which will be described later. At the moment we are dealing with broad, general principles only.

Winding Diagrams.—In any actual practical case it is desirable that the whole scheme of winding should be worked out and not merely indicated, as in Figs. 47 and 48. There are several ways in which the results of such a working out may be recorded. For instance, a winding table such as is given and explained on page 65, may be used, and this is perhaps the simplest way of issuing instructions to the workshop. Winding diagrams, however, give the designer a much better grip of the problem and enable him to see more clearly the effect of his combinations. There are several methods of drawing out such diagrams; the chief ones now employed may be conveniently referred to as (1) the *end-view*, (2) the *developed*, and (3) the *radial*.

An *end-view* diagram has already been given in Fig. 46. In this

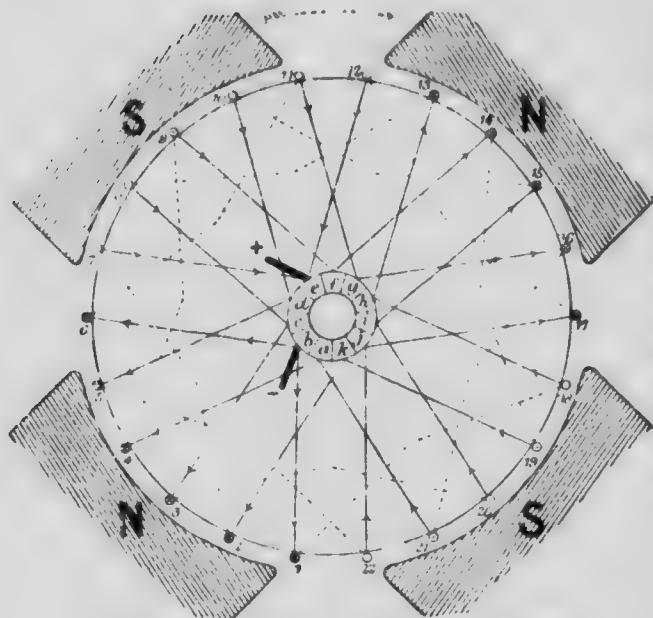


Fig. 49.—End-View Diagram of a Four-Pole Wave Winding.

for a four-pole machine and a wave winding, is given in Fig. 49, for which and the three following figures the author is indebted to the courtesy of Dr. S. P. Thompson. In this diagram the front or commutator end connections are shown with full lines and the back connections at the other end with dotted lines.

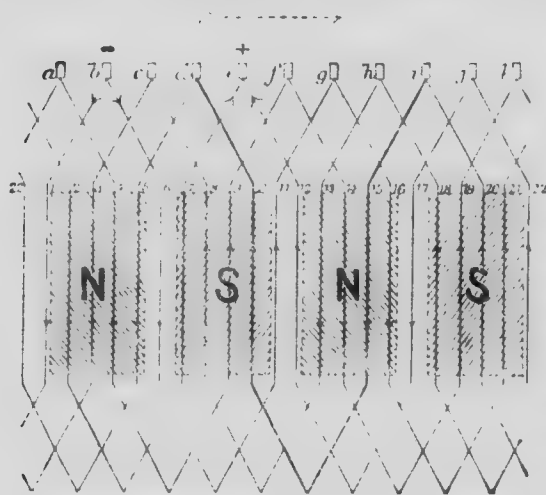


Fig. 50.—Developed Diagram of a Four Pole Wave Winding.

method of drawing out a diagram the conductors are shown in section lying on the surface or in the slots of the armature. In Fig. 46, which is for a bipolar machine, the poles are not shown, but it is desirable always to indicate these and, indeed, to avoid mistakes, it is necessary to do so in multipolar machines. Another example, this time

for a four-pole machine and a wave winding, is given in Fig. 49, for which and the three following figures the author is indebted to the courtesy of Dr. S. P. Thompson. In this diagram the front or commutator end connections are shown with full lines and the back connections at the other end with dotted lines. The particular diagram has been selected to show how with a multipolar machine it is possible to arrange the connections so that the number of pairs of brushes may be fewer than the number of pairs of poles, the number of conductors in series and the voltage being thereby increased. In Fig. 49 there are two brushes for a four-pole

me, and the reader should trace out carefully the sequence of the
 tors so as to understand thoroughly the system followed. It would
 a useful exercise for him to construct a winding table for this
 similar to that shown on page 65.

The principle of *developed* diagrams has been used in Figs. 47 and 48,
 these diagrams are purposely incomplete, so that the distinction between
 lap and wave winding might be more clearly followed. The complete

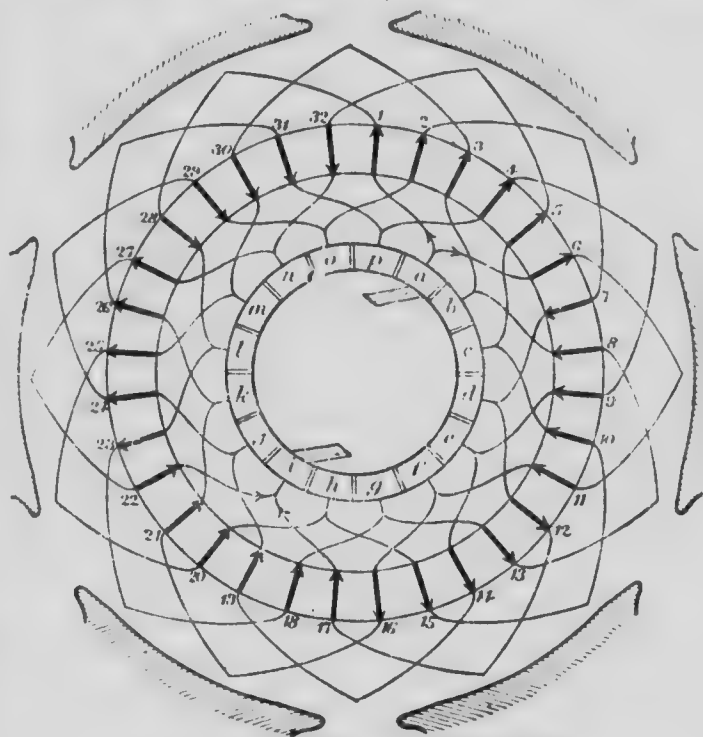


Fig. 49.—Radial Diagram of a Six-Pole Winding.

developed diagram for the same winding as that shown in Fig. 40 is given
 in Fig. 50, which will be found to be derived from Fig. 49 by supposing the
 cylindric surface of the armature, as viewed from the inside, to be divided

between conductors No. 1 and No. 22, and then unrolled and laid out flat,
 with its conductors lying on it in their proper places. The four polar
 surfaces appear as a background, and the end connectors are laid out as
 broken, sloping lines on the same flat surface. The commutator bars
 appear in section at the top of the diagram, and the positions of the two
 brushes are indicated by the signs $\oplus$ and $\ominus$.

The last form of diagram to which reference need be made, the *radial* diagram, is illustrated in Fig. 51. In this form the active conductors are shown as short radial heavy and numbered lines between two concentric circles, and the commutator bars appear between two inner concentric circles. The connectors at the commutator end are shown in the annular space between the commutator and the active conductors, and the connectors at the back end are shown outside the active conductors in the polar gaps, which are shown diagrammatically quite wide. Here again an example of a multipolar wave winding has been selected on which there are two brushes only for a six-pole machine. It will be a useful exercise for the student to trace out

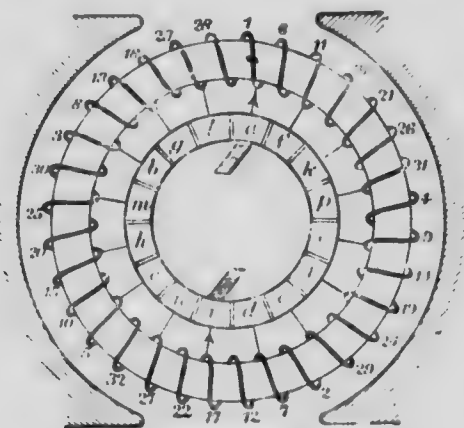


Fig. 51. Bipolar Ring Winding Equivalent to the Six-Pole Wave Winding.

this winding also in detail, and to assist him Fig. 52 gives the equivalent ring winding, which is for a bipolar machine with the corresponding conductors differently arranged relatively to one another. The same letters and numbers are used in the two diagrams, and in Fig. 52 the step from one conductor to the next is obtained by adding five.

Many other interesting points arise in working out winding schemes for specific cases, but considerations of

space will not allow us to pursue the subject farther. For similar reasons, and also because they are chiefly of interest only to designers, we pass over mathematical winding formulae which in themselves are not difficult to follow.

Driving the Conductors.—Attention will be called later (*see* page 129 *et seq.*) to the necessity for transmitting to the core discs the turning torque applied to the shaft by the prime mover, but it is further necessary to ensure that the driving forces are safely transmitted to the conductors by good mechanical arrangements. It has also been pointed out that in slotted and tunnelled armatures the forces acting on the conductors are not so great as with smooth-core armatures, for in the former a greater proportion of the magnetic drag is taken up by the iron of the core. It thus perversely happens that in the very machines in which it is mechanically easiest to drive the conductors directly by the iron of the core the necessity for

driving diminishes almost in proportion as the ease with which it is accomplished increases. In fact, in slotted armatures the designer's attention is more directed to the necessity for guarding against the effects of centrifugal force than to the necessity for driving the conductors tangentially. The tendency of the conductors to fly out of the slots is usually counteracted by wooden wedges driven under projections of the teeth, or by binding wires wrapped round the completely wound armature, as already explained. With straight-sided rectangular slots the latter device can be employed.

It is, however, different with smooth-core armatures. Here the conductors, if placed simply side by side on the turned core, can only receive from the core the forces which drive them through the field by the frictional grip which they have on it. Moreover, these forces are those due to the full flux of field and the full current, and are therefore large. With ring windings the frictional grip is obviously better than with drum windings, but in the early days even ring armatures had their conductors displaced by the magnetic drags to which they were subjected.

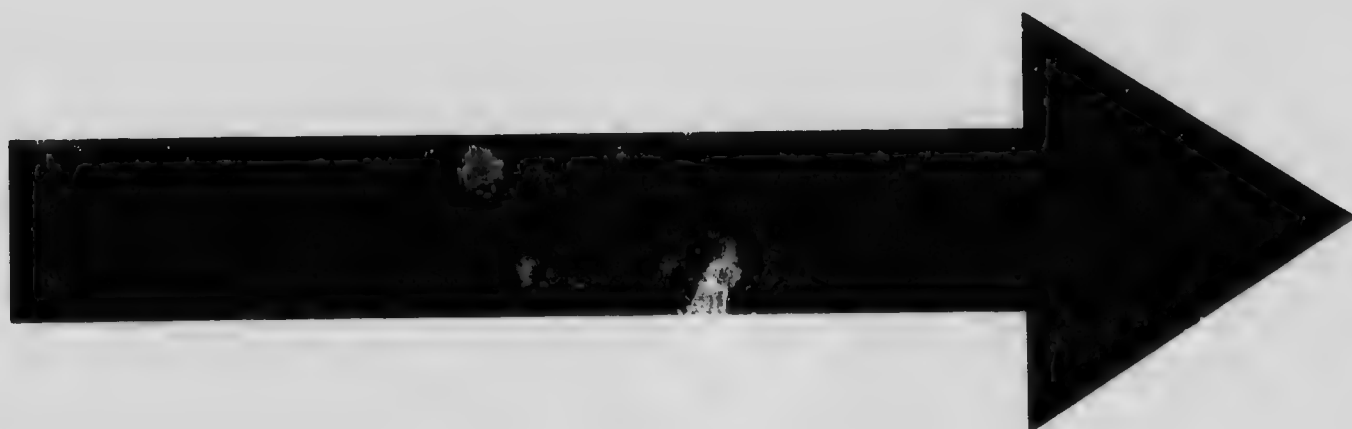
In all modern smooth-core machines, therefore, special attention is paid to this problem. A common method is to insert driving wedges of hard wood or fibre at intervals, the inner ends of the wedges usually passing down between the core discs into appropriate spaces.



Fig. 53. -Driving Smooth-Core Conductors.

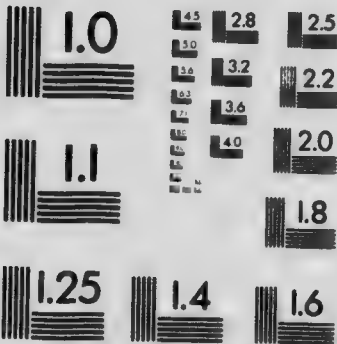
Another method is to place at intervals strips of hard fibre of the full length of the armature, the inner edges of the strips being recessed in key ways cut in the surface of the armature core. In the diagram of the magnetic circuit of an overtype dynamo, given in Fig. 4, six of these driving strips are shown in section. The method wastes some of the space in the active transmuting zone of the machines, and to avoid this some manufacturers have replaced the non-conducting driving strip by a specially deep conductor *d* (Fig. 53), which, projecting down into the iron bed, helps to give the requisite mechanical drive.

In all these cases binding wires must be used to counteract the effects of centrifugal force, and these binding wires materially help to counteract the effects of tangential drag. They usually consist of a number of turns of strong steel wire, about No. 26 s. w. g. (18 mils in diameter), wound closely side by side, and carefully sweated at the ends so as to form a continuous band. They are well insulated from the copper and iron, first by a layer of insulating tape and then by pieces of mica. A completed smooth-core armature is shown in Fig. 54, which represents an armature built by Messrs. Thomas Parker, Limited, of Wolverhampton.



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Ring v. Drum Armatures.—At first sight the drum or cylinder method of winding the armature of continuous current machines would appear to be unnecessarily complicated, and to possess serious disadvantages when compared with the simple and easily understood ring winding. The chief difficulties of the method have already been briefly explained (*see* page 493, Vol. I.). The chief advantage, as compared with ring winding, is the reduction of the ratio of the length of idle or dead wire to that of active wire. In a ring armature the whole of the wire on the side of the ring remote from the magnet poles, as well as that on the edges of the ring, is so much dead wire, only required to make the necessary electrical connections, and contributing nothing to the E. M. F., but adding very appreciably to the resistance of the machine. Where, as in the usual case, the poles face one of the longer surfaces of the ring only, this dead wire must at least be greater in length than the active wire, and consequently the

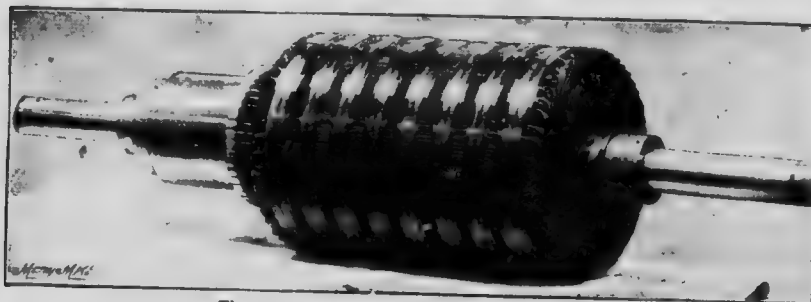


Fig. 54.—Parker Armature with Eickemeyer Coils.

total energy wasted in heating by the passage of the current will be more than double that wasted in the active part of the wires.

Another advantage of the drum method of winding is that the inductance of each section of the winding between successive commutator bars is less than in a ring-wound armature, for the wires do not so completely enclose the iron core, especially in multipolar machines. This lessening of the inductance leads to two desirable results. In the first place, sparkless reversal of the current in the coils under the brushes is facilitated; and, secondly, the reaction of the armature current on the field is diminished. Incidentally we may remark that in another way the drum-winding renders possible a reduction of the armature reaction.

On the other hand, the drum-winding is not so simple as the ring, and requires greater care in winding, as there is a possibility of making serious mistakes in connecting up the successive coils. This disadvantage can obviously be overcome by systematising the work, issuing careful winding instructions, and employing intelligent workmen. Winding tables and winding diagrams for this purpose have been referred to above. Again,

the insulation of the windings is more difficult, especially in those machines in which the wires or bars are laid on in a single layer, for this necessitates the placing alongside one another of bars connected to electrically opposite sections of the commutator, and between which there is at times a P. D. equal, or nearly equal, to the full E. M. F. of the machine. An examination of Figs. 46 and 51 will show how this is inherent in the schemes.

It is also more difficult to ventilate a drum than a ring armature, for it is obviously necessary to keep the conducting wires as cool as possible

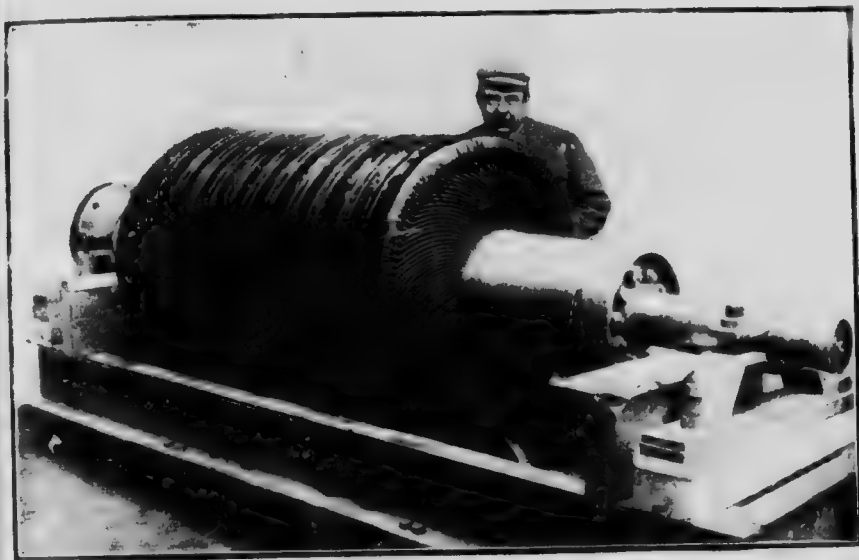


Fig. 55.—Crompton Armature with Spiral End Connections.

by carrying off the ohmic heat rapidly. For this purpose special ventilating ducts have to be arranged in drum armatures, especially in large machines.

Lastly, owing to the crossing of end connections, the repair or replacement of burnt-out or damaged coils is more difficult in drum- than in ring-wound armatures. In modern machines this important question of repairs is kept carefully in view in designing the end connections, which, it is needless to say, are now always arranged on a definite plan, and not bunched up haphazard as in the early machines.

End Connections of Drum Armatures.—It thus happens that a very important part of the design of a drum-wound armature is the arrangement for making the connections of the various conductors to one another at the two ends of the core. We have explained (see page 523, Vol. I.) how Edison solved the problem in his early dynamos, and obtained

low resistance for the connections by using copper discs. He also, as described in a previous edition of this book, used insulated circular sectors, placed at the two ends; to each sector one of the conductors was soldered, and the proper sectors were connected by concentric circular segments of different radii.

Siemens used curved connections in two layers, each complete connection at the back end (i.e. the end remote from the commutator) consisting of one curve in the outer layer and the other in the inner, the two being joined together at a central wooden hub.

Later Swinburne and Crompton employed carefully shaped spiral connections (Fig. 55). In applying these to a bar armature the bars were made with projections beyond the core alternately short and long. The

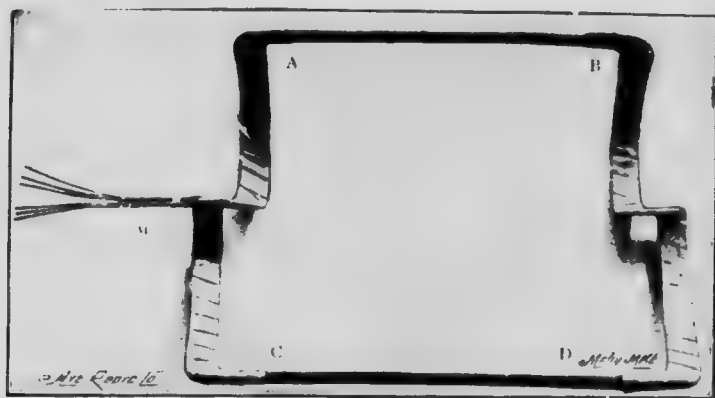


Fig. 56.—Kickemeyer Coils for Parker Dynamo.

former were joined to an inner layer of spirals twisting in one direction (e.g. left-handedly), whilst the latter were attached to an outer layer twisting in the opposite direction (or right-handedly).

Kapp used a modification of the Edison disc with projecting lugs in which the greater part of the disc was cut away, leaving a broad semi-circular or quadrantal arc, and the lugs were twisted at right angles to the plane of the arc, so that they could be slipped into slots in the armature bars.

Former-Wound Coils.—A method of arranging the connections of drum-wound armatures which is now widely used in this country and abroad, especially for machines in which the single conductors do not carry heavy currents, consists in winding and insulating the coils separately before placing them on the core. Each coil may consist of a single turn of thick wire or of several turns of finer wire, and in some cases the separate turns of a coil are joined in parallel. A very convenient shape to give

the finished coil was devised by Eickemeyer, and is shown in Fig. 56, a form which was used by Messrs. Thomas Parker, Ltd., of Wolverhampton and many other firms. This coil is usually employed in slotted armatures in which the conductors in each slot have two positions (see Fig. 56), an upper and a lower, but in this case it was used with the conductors side by side for the smooth-core armature already illustrated in Fig. 54. The active parts of the coil are A B and C D, of which A B would be in the bottom of the slot, with the C D of another coil above it. The

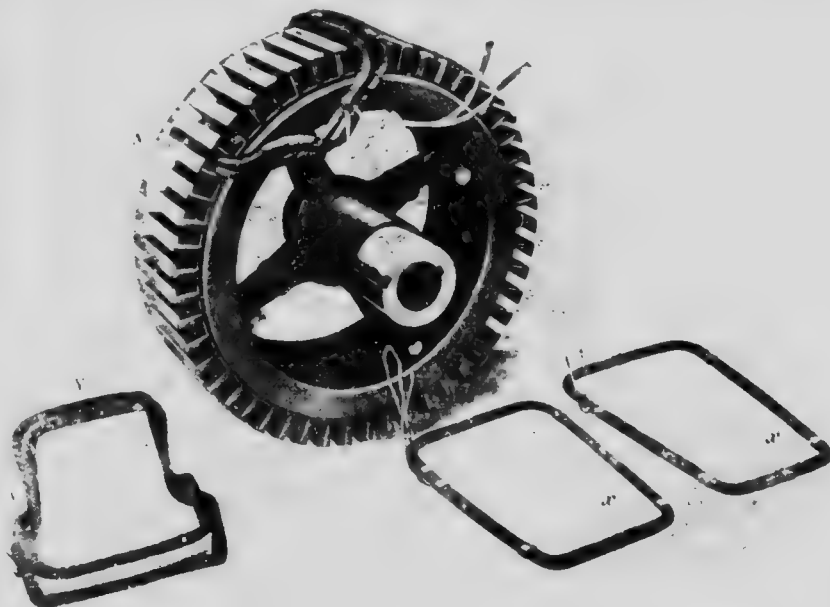


Fig. 57.—Method of Winding Armature Coils and Placing them on the Core (Lap Winding).

connections at the back of the armature appear at the right-hand side of Fig. 54. By carefully comparing these with Fig. 56 the way in which the inner and outer connections pass one another will be understood. This important point is even more clearly illustrated in Fig. 57, which represents two such coils being placed on a motor armature. The two shorter sides of the coils lie in the bottom of the slot on the left at A, and the two longer sides will be placed home in the top of the slot on the right when the two shorter sides of another pair of coils have taken their places below them.

The various methods by which the coils are formed are interesting. The two stages adopted are shown in Fig. 57. Trapezoidal-shaped plane coils *xx* are first wound, the parallel sides of the trapezium being the

longer and shorter conductors of the finished coil: These plane coils are then placed on formers, and shaped as shown at *Y*. They are then carefully insulated with layers of oiled muslin and tape applied by hand.

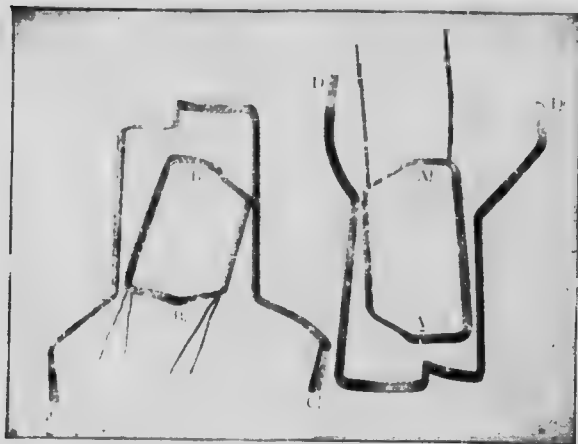


Fig. 58.—"Former" Coils for Wave Winding.

being used is shown in the upper part of Fig. 59. For larger machines each coil consists of a single conductor either made up of strips of copper placed electrically in parallel, as in *C*, or of a single bar of copper forged to the required shape, as in *D*. These strips or bars are carefully insulated before being placed in position, and the connecting strips at the corners at the commutator end are bent outwards instead of inwards, thus increasing the span of each "wave." The lower armature in Fig. 59 shows coils similar to *C* and *D*

(Fig. 58) being placed on the core. In this as well as the preceding case, and as previously explained, the winding is in two layers in the slots, the shorter conductor of the shaped winding of Fig. 58 being placed in the lower part of the slot, and the longer conductor in the upper part of the corresponding slot at about the polar pitch farther on. The only junctions

For wave winding the Westinghouse Companies use the coils shown in Fig. 58, in which there are four coils, *A*, *B*, *C*, and *D*, for different sizes of machines. For the smaller machines each coil *A* or *B* has several turns, and the ends are brought out at the two corners on the same side of the coil. A partially wound armature in which such coils were

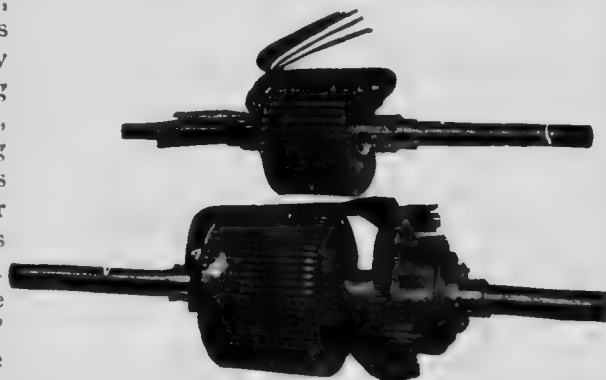


Fig. 59.—Partially Wound Westinghouse Armatures.

in the machine are the connections to the lugs of the commutator; the conductors are held in the slots partly by the overhang of the teeth at the top of the slot, wooden wedges being driven in to tighten up. In addition, fine wires, well insulated from the conductors, are bound tightly to the finished armature. Fig. 60 shows the two finished armatures, with binding wires, etc., ready to be placed in the machine.

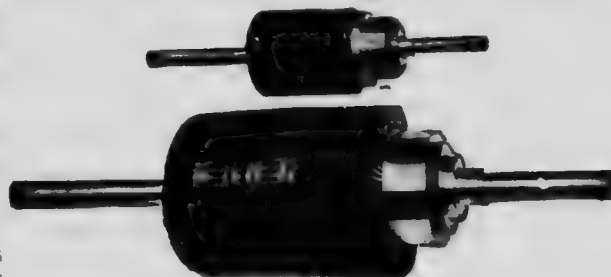


Fig. 60.—Completed Westinghouse Armatures.

A wound armature as built by Messrs. Crompton and Co., in which former-wound coils are used instead of the spiral end connections of Fig. 55, is shown in Fig. 61. The core is slotted with open slots into which the wound coils can be introduced after being wound, and in which they are held in place by wooden wedges and the usual binding wires, of which there are three bands on the core itself and two others, much wider, holding the connections in place, besides an extra

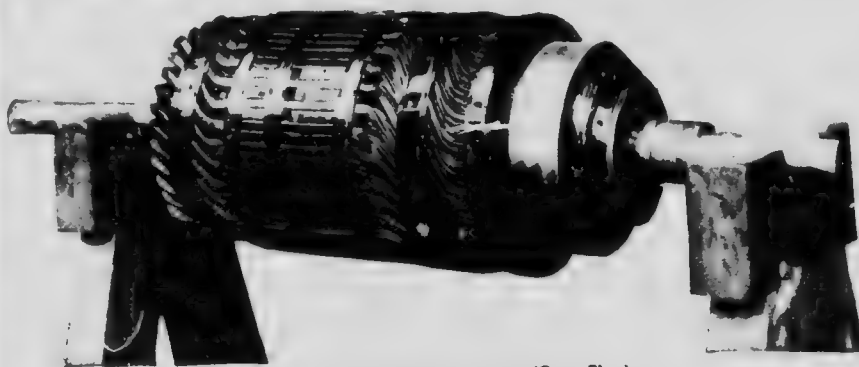


Fig. 61.—Wound Crompton Armature (Open Slots).

band bound over the junctions between the commutator and armature connections. The wedge method of holding the windings in the slots is further referred to at page 87.

As a contrast to Fig. 61 there is shown in Fig. 62 an armature built by the same firm in which the core slots are nearly closed, so much so that former-wound coils cannot be introduced into them. The windings must therefore be threaded through the slots, the end connections being

designed for this condition. As against the greater labour involved in this method of winding, it should be noticed that no wedges or binding wires are used on the armature core to hold the windings in their places, this being done effectively by the overhung parts of the core teeth. Binding wires, however, are still required to hold the connectors in their places.

It will be obvious that the winding methods used in Fig. 62 are chiefly useful for heavy-current low-voltage machines in which the individual conductors have a large cross-section, whether solid or laminated, and that the open-slot method of Fig. 61, with its former-wound coils, is better adapted to small-current machines of higher voltage, having several turns per commutator section, the individual conductors being much lighter. We have here an instance of how the actual form of the output (i.e. whether low or high voltage) for a given size of machine modifies the details of the



Fig. 62.—Wound Crompton Armature (Semi-Enclosed Slots).

design. Another modification, which will be dealt with in detail later, is seen in the very different lengths of the commutator bars, which are long in the case of the heavy-current armature (Fig. 62) and short in the case of the lighter-current armature (Fig. 61).

In several of the types described above the end connectors, of whatever pattern, have one feature in common—namely, that in making the connection from one conductor to another they dip more or less radially inwards, and thus shorten, sometimes nearly to the vanishing point, the connecting strips at the commutator end between the commutator bars and the windings of the armature. This dipping over of the end connections has the disadvantage that the repairs of damaged windings are difficult, as the taking out of a coil disturbs many of the other windings and is a laborious process. But there is another general method of construction widely employed in which the whole of the connecting strips, of whatever pattern, are contained within a shallow cylindric—or, more strictly annular—space of radial depth little greater than that of the slots. Such

... necessitates either long radial connectors between the commutator bars and the windings, or a commutator with a diameter nearly equal to that of the armature. Each of these, and intermediate modifications, are used in modern machines.

An example of such construction, Fig. 63 shows the armature of a Mather and Platt dynamo similar to, but somewhat smaller than, the

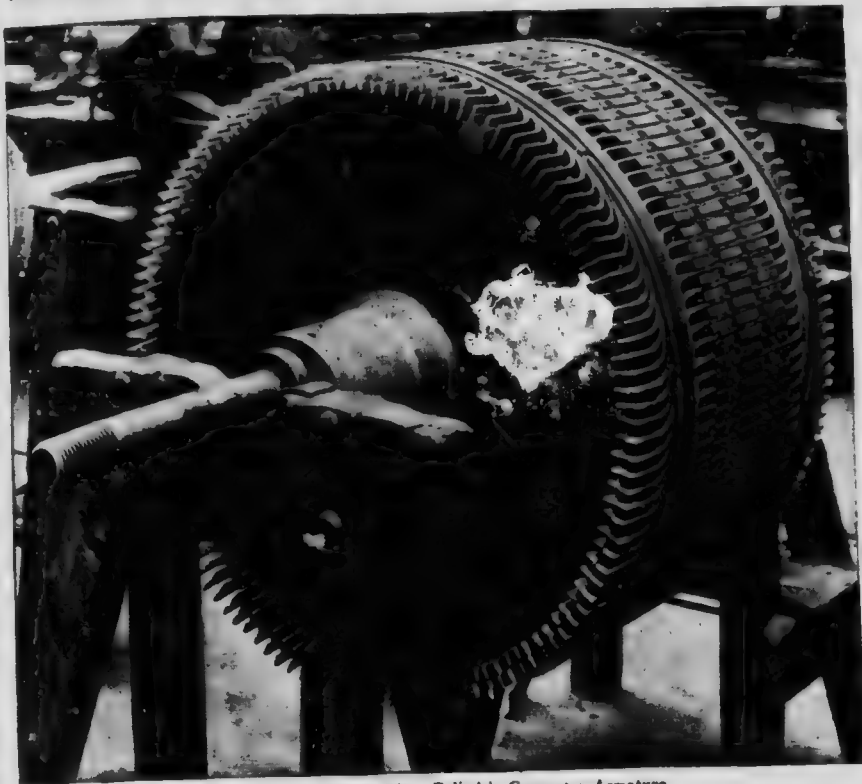


Fig. 63.—Mather and Platt Cylindric Connector Armature.

machine which has been described at page 18. The armature illustrated is completely wound, but the commutator has not yet been fitted to it. The core plates, as can be seen, are mounted upon a cast-iron four-armed spider, and are firmly clamped together with steel bolts and nuts between stout cast-iron end plates. There are two ventilating ducts, and the details of construction have been carefully designed to secure excellent ventilation so that the armature is kept cool at top loads.

The bars of the armature have their ends bent round in opposite direction, each end thus covering about half the peripheral distance to the bar

to which it is to be connected. There are two bars per slot, the ends of the lower bars being kept in the direction opposite to those of the upper, so that the last few inches of each bar being brought parallel to the axis, the bar ends can be sweated or soldered together, and the final connection made according to winding schemes already explained. The parts of the bars between the core iron and the soldered connections are very securely held in place with steel wire bands. It will be observed that the method materially increases the axial length of the outer periphery of the full diameter of the armature and, consequently, of the whole machine as compared with the methods in which the connectors are more radial. Thus in the example just given, the full axial length from tip to tip of the copper bars is more than three times that of the core plates alone. This, however, does not seriously add to the cost of construction, and the type of winding has obvious advantages.

The method, moreover, has so many advantages that in applications of



Fig. 64.—"Former" Windings being Fitted on Core with Cylindric Winding Drum.

it in which the actual windings have not, as in Fig. 63, the necessary stiffness, two "winding drums," as they are called, are added, on which the end connections can lie and be held in their places by appropriate binding wires. The use of such drums or cylinders has led to the method being known as "cylindric" or "barrel" winding, the chief feature being that the end connections lie on a curved cylindric surface and not on the radial end surfaces of the armature. The coils, placed as described, are much more easily accessible in the event of a breakdown, and the connecting up, etc., is also easier. On the whole, the advantages are so important that many modern machines, especially for large sizes, are wound in this way. The winding drums referred to, or the equivalent space, can be seen in several of the illustrations of armature cores given elsewhere in the book—for instance, in Figs. 66, 67, 69, 70, 90, 95 and 120. As an additional instance, Fig. 64 shows a "former" winding of the cylindric type being fitted on to the core of an armature for a dynamo built by Messrs. Scott and Mountain. The winding drums are clearly shown, and an interesting feature is that there are no ventilating ducts in the iron.

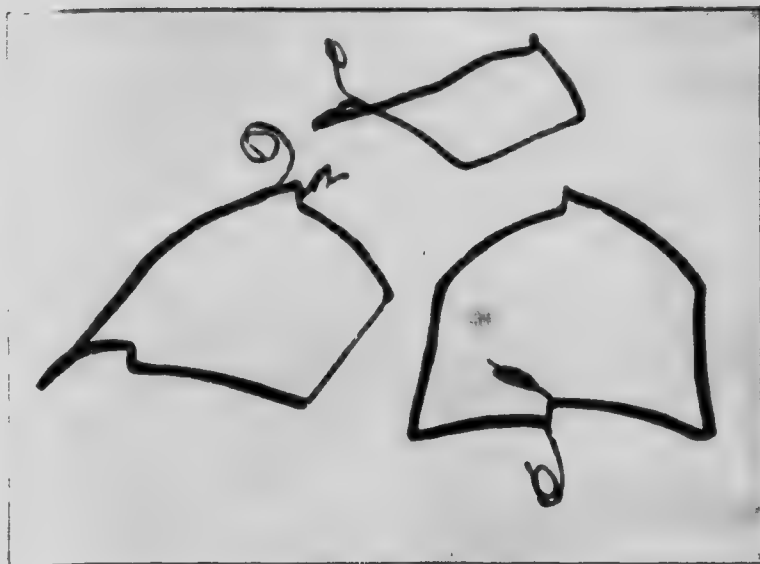


Fig. 65.—"Former" Coils ready for placing on Core.

The coils for this type of winding, as used by Messrs. Scott and Mountain, are shown in Fig. 65, which should be compared with Fig. 64.

The cylindric mode of end connection can be employed for either lap or wave winding in multipolar machines, according to the way in which the ends are brought out. The coils shown in Figs. 64 to 66 have the ends of the windings brought out at the same point of the coil; these ends being joined to successive bars of the commutator will give a lap winding. Fig. 66 shows such a

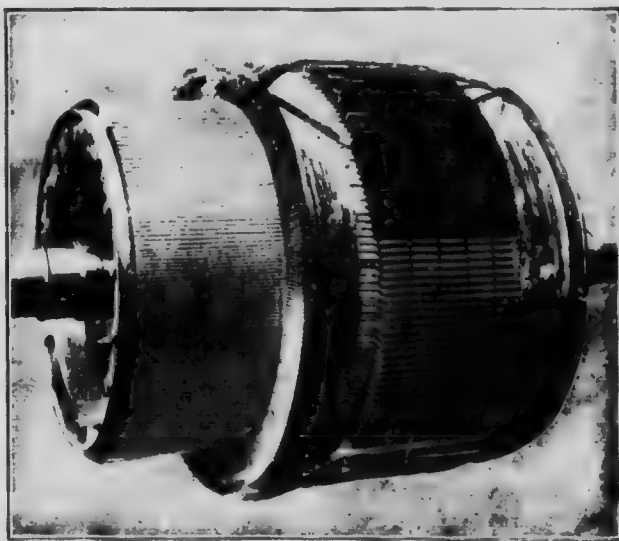


Fig. 66.—Lap Winding with Cylindric Winding Drum and End Connectors.

winding being applied to the armature of a large eight-pole machine, as built by the International Electrical Engineering Company of Liège.

The manner in which the successive coils follow one another round the armature can be easily traced. In this case each coil consists of a single turn, and the two ends, though quite differently shaped, are brought out at the place corresponding to *M* in Fig. 56. Of these ends the one nearest the side *AB* is always let into the bottom of the slot in the lug of the commutator, and the other end slips into the top of the slot of the next following lug. The conductors are insulated by being overwound

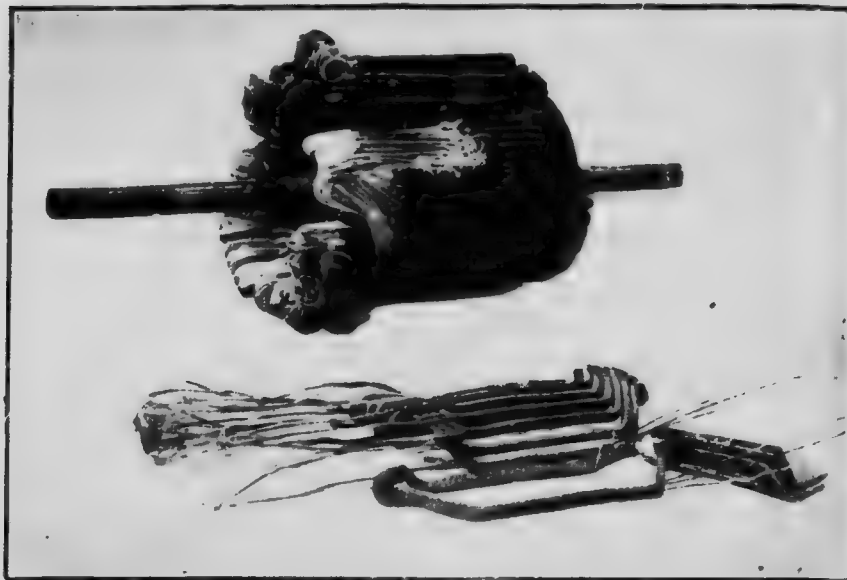


Fig. 67.—"Former" Wound Coils and partly wound Bruce Peebles Armature.

with tape, etc., but in addition there can be seen in Fig. 66 the **U**-shaped channels of micanite or other insulating material which are placed in the slots so as to insulate further the conductors from the iron. The machine is for an output of 300 kilowatts (400 E. H. P.), and note should be taken of the substantial character of the commutator, the length of the bars being about equal to the polar length of the active conductors.

A pattern of "former"-wound cylindric coil adopted by Messrs. Bruce Peebles and Co., Ltd., some years ago, and still substantially the same as the coils now used, is shown in Fig. 67 together with a partly wound core. The five or six coils on the ground show very clearly how they lie side by side on the armature, and the reason for the peculiar shape given to the end connections. Each coil consists of five turns of three strips in parallel, as

the machine is intended to develop 230 volts at a speed of 650 R. P. M., the output being 12 kilowatts. The whole coil is very carefully taped and insulated, and also well baked before being placed on the core. The completed armature is shown in Fig. 68.

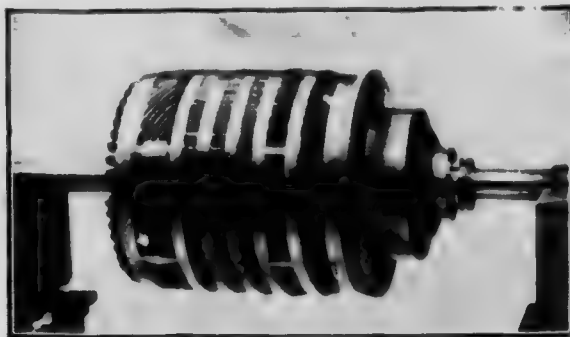


Fig. 68.—Bruce Peebles Armature completed.

The commencement of the winding of a large multipolar drum armature is admirably shown in Fig. 69, which represents, in process of construction, the armature of a 750-kilowatt dynamo built by Messrs. Bruce Peebles & Co. to give, at 180 R. P. M., 500 to 550 volts as a traction generator. Four sets of

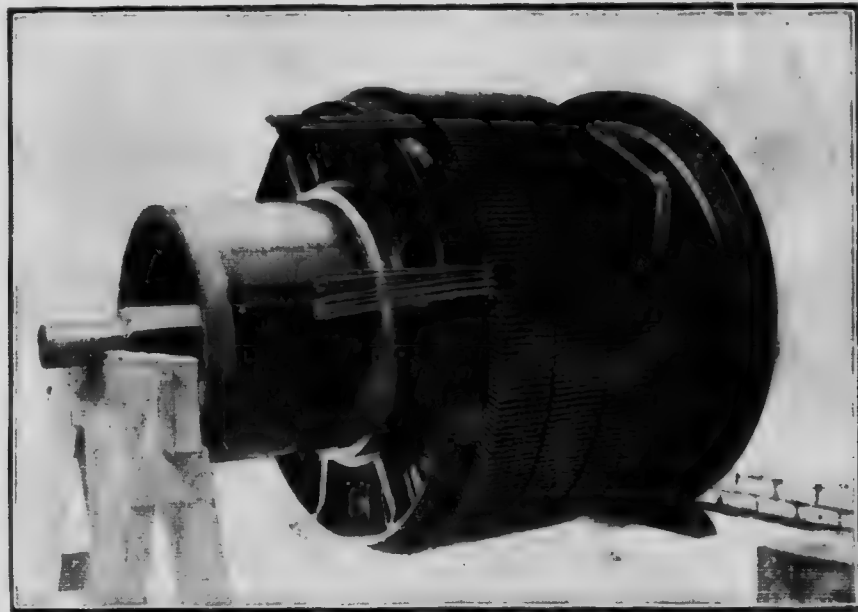


Fig. 69.—Commencement of Wave Winding a 750-Kilowatt Armature.

former windings, each consisting of two insulated copper strips, are shown placed consecutively in the slots, from the iron of which they are insulated

by U-shaped grooves of micanite or other insulating material. Although previously referred to, attention may be again called to the armature spider and the core. The former is continued at the back end, not only to provide the winding drum, but also to furnish a coupling to the fly-wheel of the engine. At the front it is extended for the winding drum, and at a smaller diameter to provide the support and drive for the commutator. In regard to the core attention should be directed to the narrowness of the

teeth and the simple shape of the slots.

A stage in the winding of the armature of a large multipolar dynamo is shown in Fig. 70, which represents an armature seen from the commutator end, with all the conductors in position and ready for connection to the lugs of the commutator. This armature is for a dynamo with an output of 1,000 kilowatts, as constructed by the International Electrical Engineering Company. The figure will give the reader some idea of the amount of detail involved in the winding part of the construction, and the care

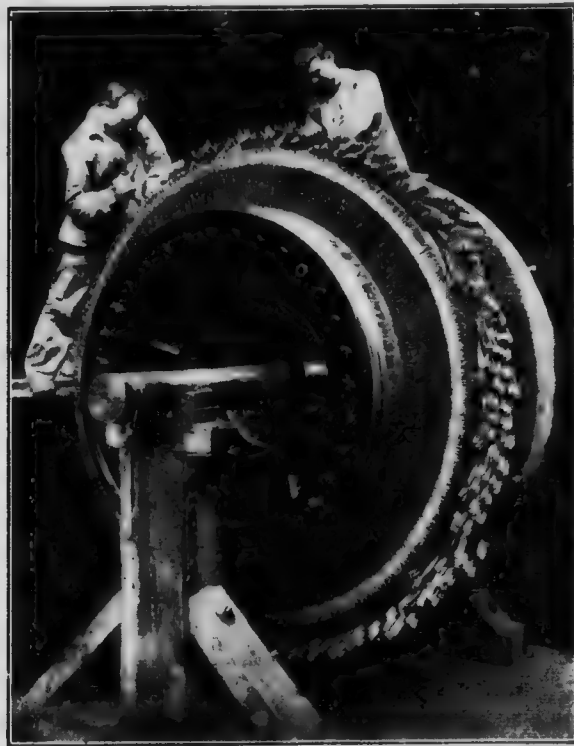
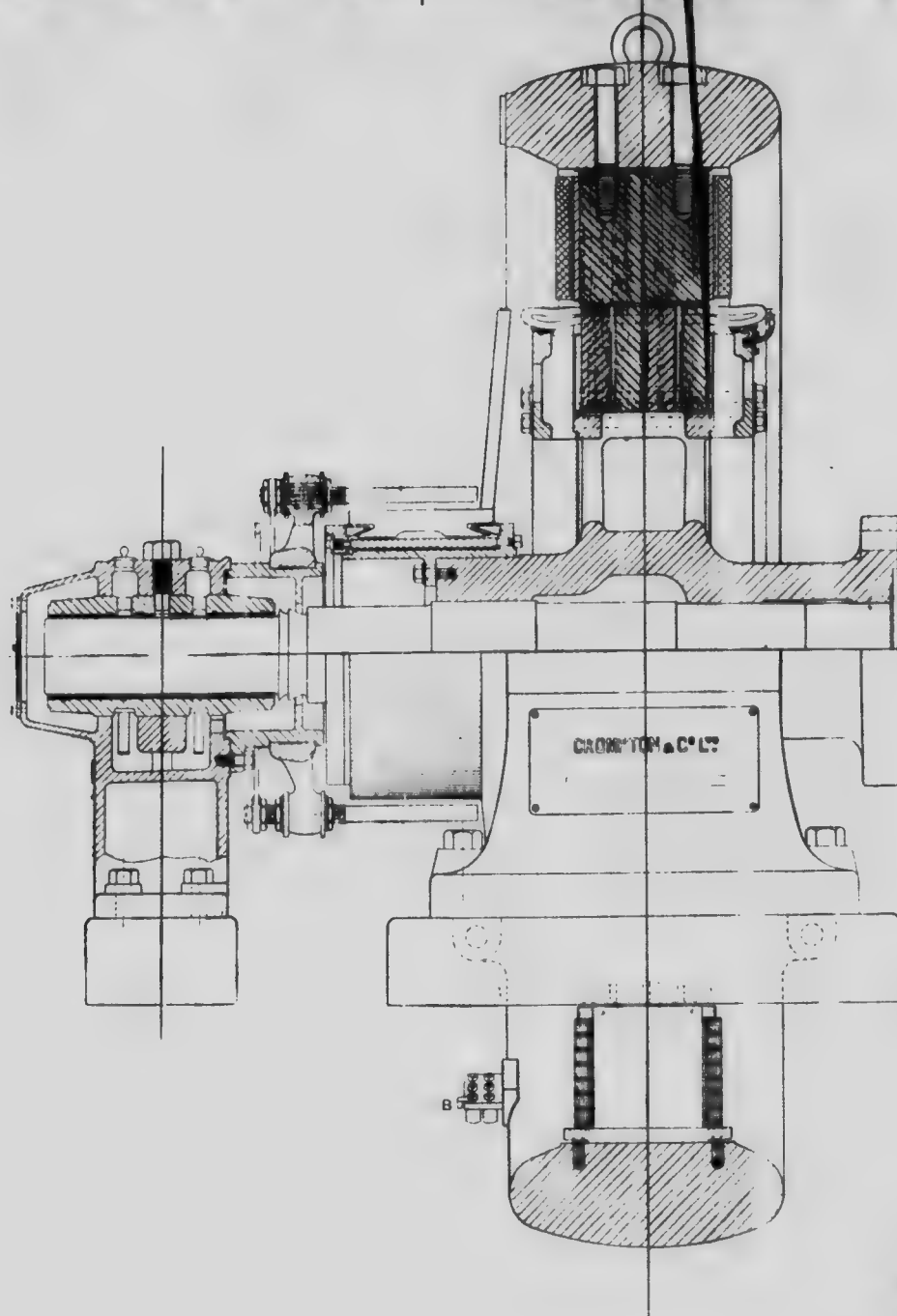


Fig. 70.—Making the Connections to the Commutator Lugs.

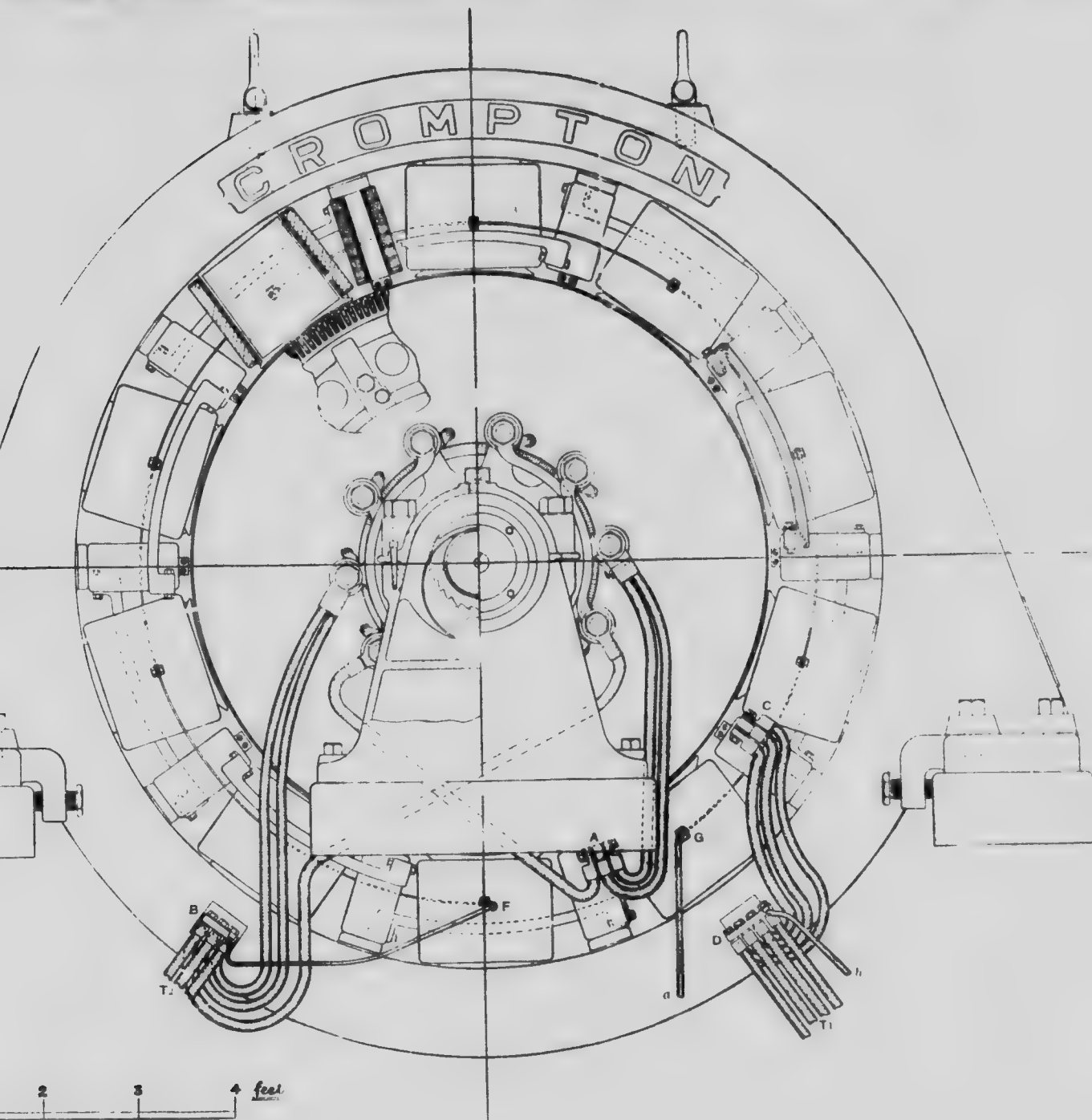
which must be exercised in planning the winding in the first instance so as to run the minimum of risk of the connectors being joined to the wrong lugs. The edges of the micanite linings of the armature slots in which the active conductors are laid can be clearly seen projecting from the slots at this stage of the construction.

The completed armature of the large multipolar dynamo built by Messrs. Mather and Platt, and whose yoke ring has already been referred to (Fig. 10), is shown in Fig. 71. This armature is built for an output of 800 kilowatts at 440 to 550 volts, and 100 revolutions per minute. The



inches





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ND 10-POLE 75

full load current will therefore be about 1,600 amperes, divided between five sets of brushes at each terminal.

Full details of a modern machine, including particulars of the armature are given in Plate III., which represents a 750-kilowatt dynamo built by Messrs. Crompton and Co., Ltd, to which references are also made elsewhere (see pages 20 and 22). The armature is slotted and is drum-wound with "former" coils, which are held in their places by long wooden wedges or keys, as shown diagrammatically in Fig. 72, where it will be noticed

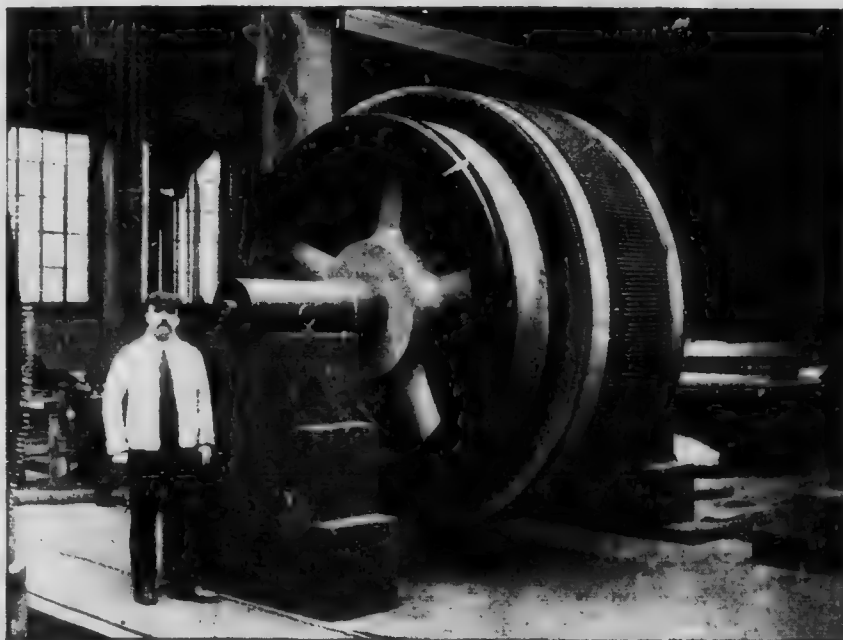


Fig. 71.—Completed Armature of an early pattern of Mather and Platt Multipolar Dynamo.

that for this purpose the teeth are undercut at the top. The wedges can be clearly seen on the figure, which is drawn to scale, full size, and their use renders binding wires unnecessary. The air-gap is $\frac{1}{4}$ of an inch from iron to iron, and the radial depth of the armature stampings is 11 inches. There are 230 slots with four conductors in each, making a total of 920 conductors, and as there are ten poles and ten circuits, each conductor will carry a current of about 165 amperes when the dynamo is loaded up to its full load of 1,650 amperes. At normal speed, 250 R. P. M., the peripheral speed of the armature is over 4,700 feet, or about 0.9 of a mile per minute. Particulars of the brush gear are given later (see page 156).

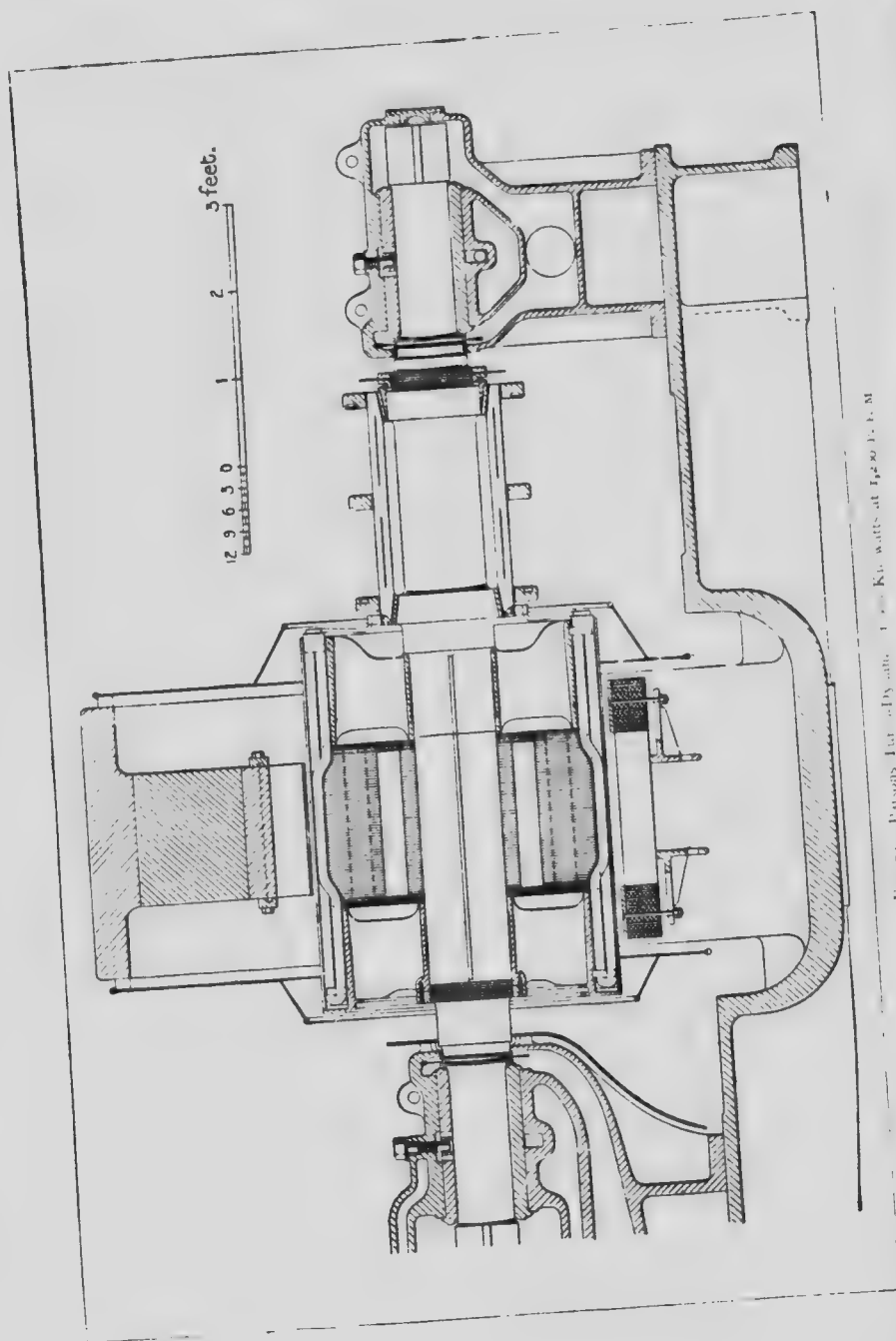


Fig. 73. - Parsons Turbine. 1000 H.P. at 14,000 R.P.M.

Fig. 73. - Parsons Turbine. 1000 H.P. at 14,000 R.P.M.

Fig. 73. - Parsons Turbine. 1000 H.P. at 14,000 R.P.M.

Turbo-Dynamo Armatures.—Attention has already been drawn (see page 13 *et seq.*) to the fact that the high speed at which turbine-driven dynamos are run profoundly modifies the design, and, as might be expected, modifications are required in the armature as well as in the other principal parts of the machine. It will, therefore, be of interest to examine one or two armatures of modern turbo-dynamos, if only to contrast them with the slower-speed armatures already described.

One naturally selects for a first example a Parsons machine, and in Fig. 73, taken from a paper read by Mr. Stoney, in 1908, before the Institution of Electrical Engineers, is shown a longitudinal section of such a machine, designed for an output of 1,000 kilowatts at 500 volts, when running at a speed of 1,200 R. P. M. The greatest contrast with the slow-speed type of machine is probably in the small proportion which the axial length

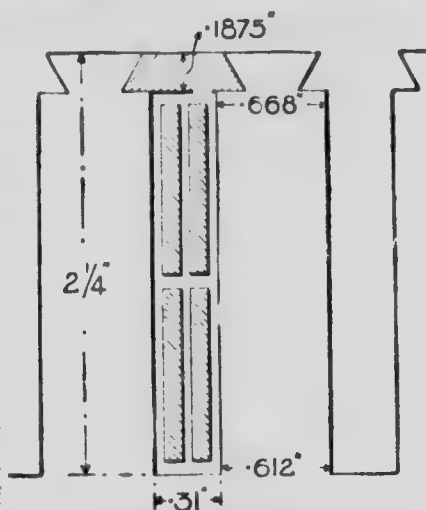


Fig. 72.—Diagram of Slot, showing Wooden Wedge and Conductors.

of the magnetic circuit, including the armature iron, bears to the over-all axial length of the machine. In the figure given it will be found that the machine, which is nearly 13 feet long, is nearly seven times as long as the iron of the armature core (23 inches). The machine is a four-

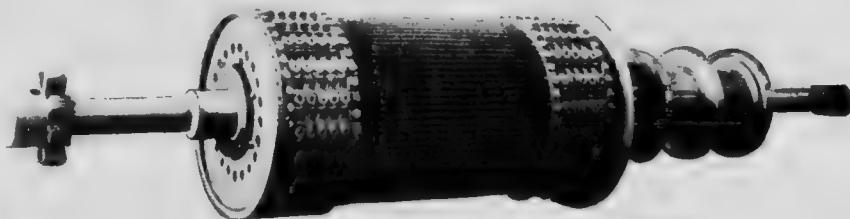


Fig. 74.—Parsons 1,000-Kilowatt Armature, with Semi-Sunk Conductors.

pole machine (see also Fig. 93), and the armature core is 36 inches in diameter. There are no interpoles, but compensating windings, to which further reference will be made later, are used on the pole faces, which ensure satisfactory commutation at 25 per cent. overload. There are 192 active conductors, and half that number (96) of commutator segments. Details of the commutator will be found at page 138.

A still more recent pattern of Parsons armature is shown in Fig. 74, which depicts the armature of a 1,000-kilowatt machine, giving 500 to 550 volts when running at 1,800 R. P. M. In the early Parsons dynamos smooth cores were used to assist the commutation by the low inductance of the windings, and in an end view and cross-section (Fig. 93) of the machine, shown in Fig. 73, the core of this dynamo is seen to be smooth. It is difficult, however, by means of binding wires and other devices to keep the conductors in their places on such a core, and in more recent machines shallow grooves were used to assist in dealing with the difficulty. In the most recent machines, however, and in the armature shown in Fig. 74, the cores are slotted with slots of a peculiar shape, three of which are shown in Fig. 75. The section of the slot may be described as a "bottle" section, since there is a narrow neck towards the exterior which widens out into an oval shape lower down. The slot so shaped is first lined with insulating

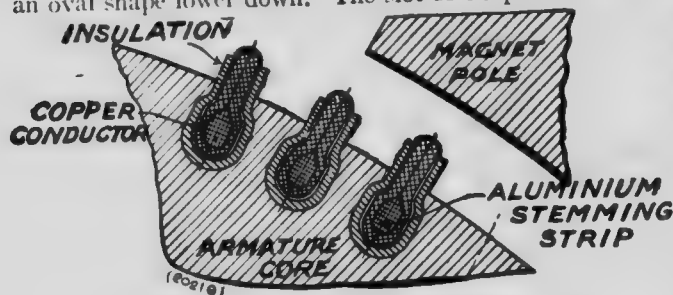


Fig. 75.—Section of Core with Semi-Sunk Conductors in Position.

material, and then a split conductor of similar shape to the slot and completely filling the neck, is pushed in from the end. When thus introduced, the copper conductor leaves still an unfilled space in the middle of the bottle section. Into this space stemming pieces, consisting of short lengths of aluminium rod, are driven, causing the split conductor to open out, and wedging it very firmly in the slot, thus avoiding any possibility of shifting. The shape of the slot counteracts the centrifugal forces, and binding wires are not required, though a considerable fraction of the copper conductor lies outside the iron of the core. Two other main advantages are secured. In the first place, the projecting copper is very well placed for being kept cool, both by radiation and by contact with cool air in the gap. In the second place, during commutation the section of the strip embedded in the iron has an inductance different from that of the part outside the iron, with the result that one short-circuits the other for the E. M. F.'s caused by the variation of current. In this way the commutation is materially assisted, making it easier to secure sparkless running.

One other point may be mentioned with reference to this interesting armature, and that is the method of securing the bar conductors to the end connectors. The latter are of the ordinary drum spiral type, to which the bars are secured by bronze bolts, giving a better mechanical result

PLATE IV

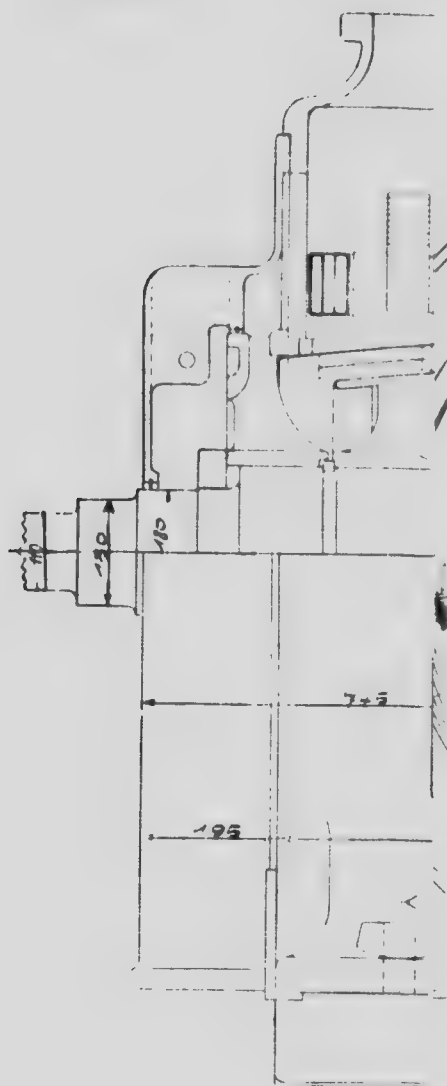
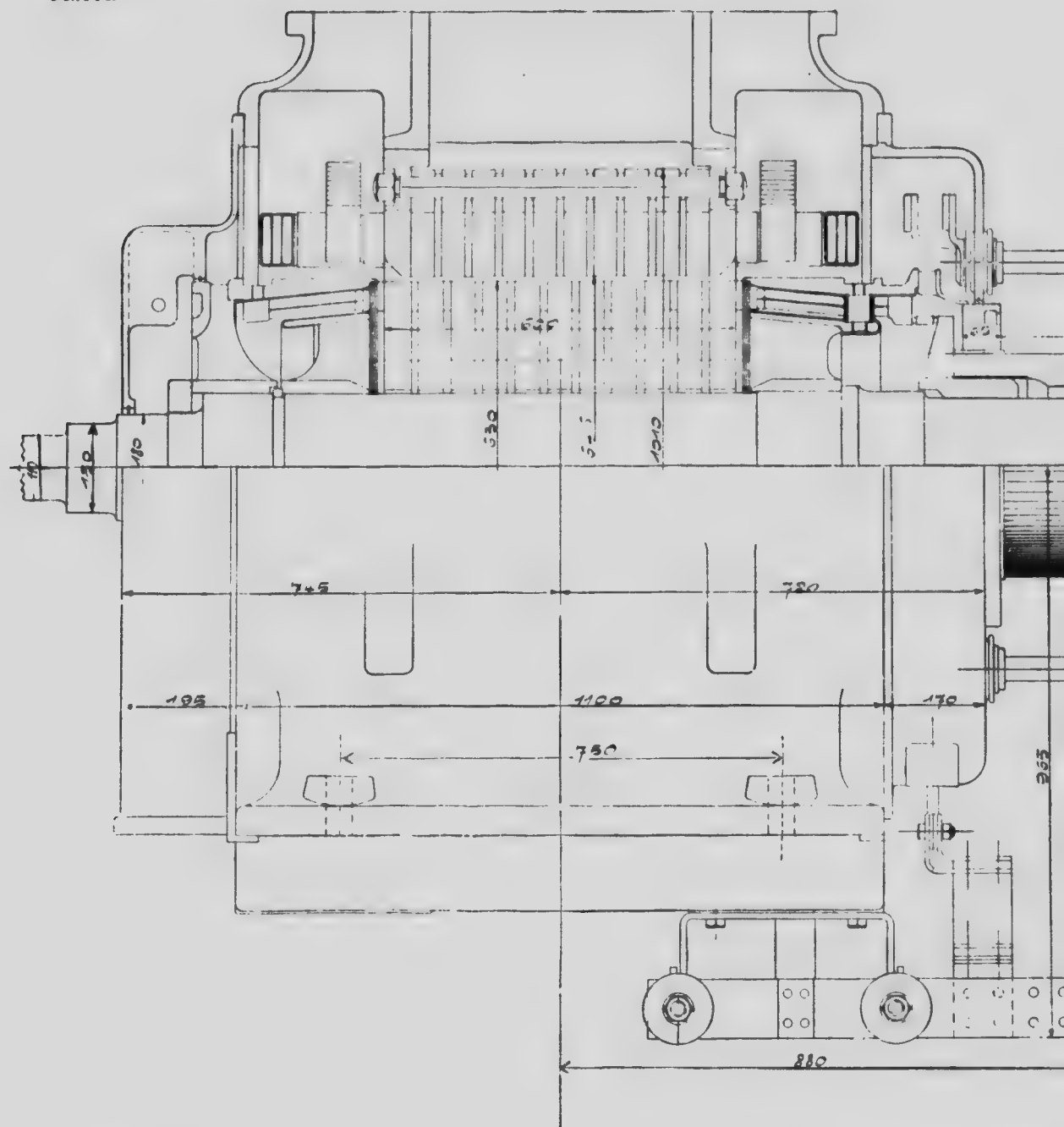
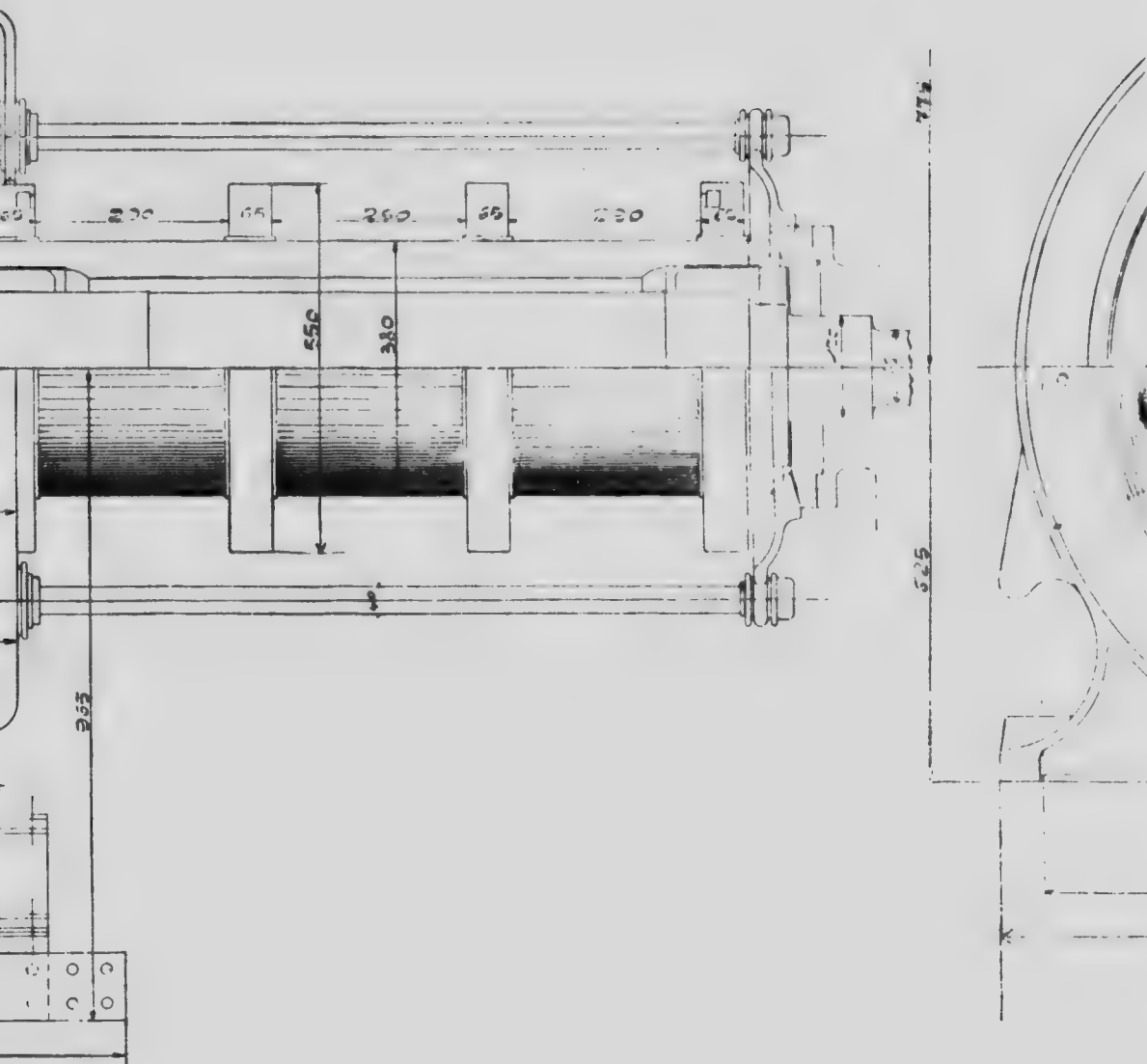
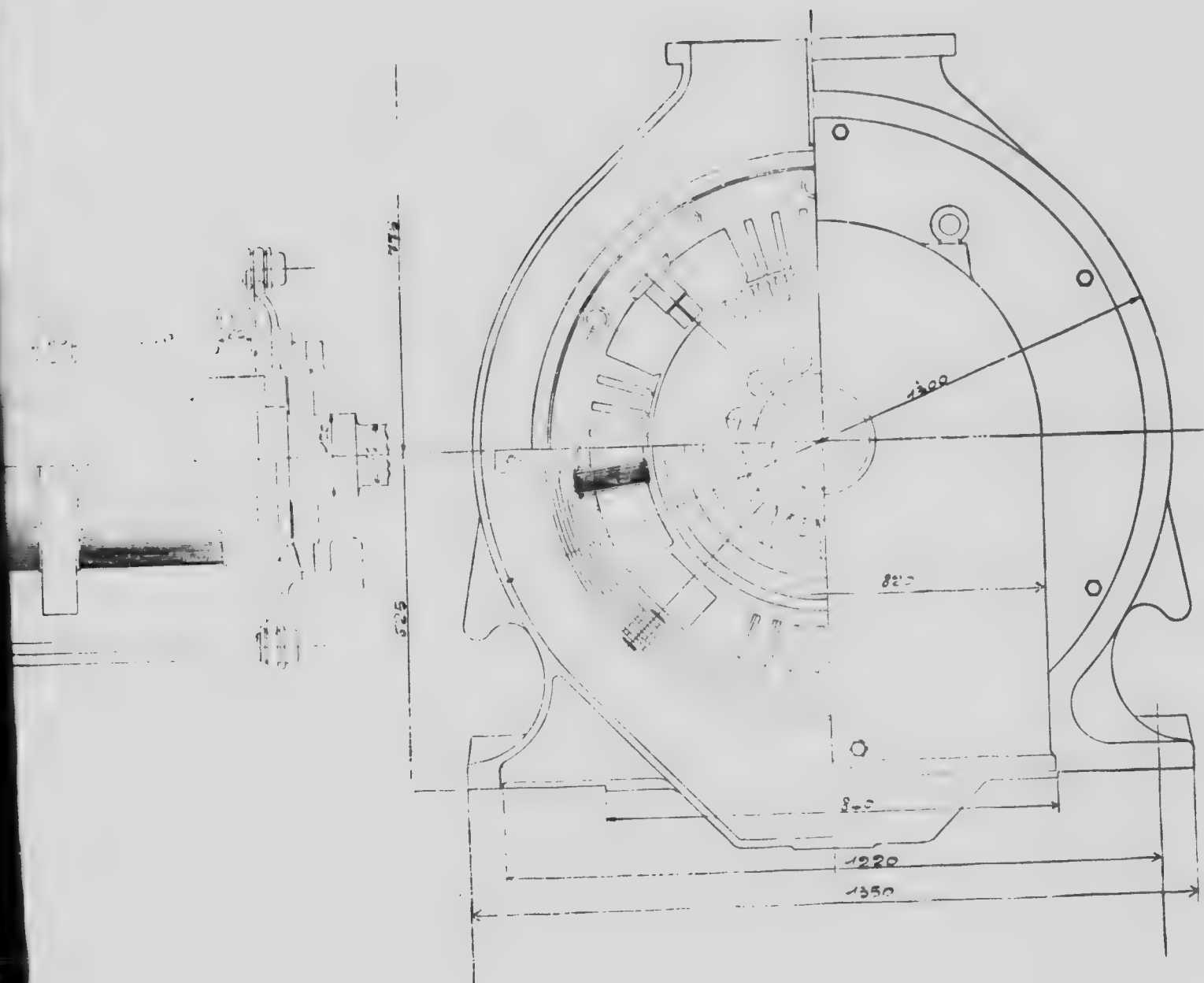


PLATE IV





BROWN, BOVERI & CO. TURBO-DYNAMO, 500 KILOWATTS, 250 VOLTS, AT 2,100 R. P. M.



KILOWATTS, 250 VOLTS, AT 2100 C. I. M.

than binding wires. It is further claimed that this is also better than the bronze end bells which are used by some constructors.

The Parsons turbo-dynamos are constructed with salient poles, and, therefore, the next example given is of a dynamo with a field frame similar to that shown in Fig. 8, the frame, when wound, presenting almost a smooth cylindric surface to the revolving armature, thus reducing the losses by windage to a minimum.

In Plate IV. are given details with the principal dimensions inserted of a turbo-dynamo, built by Messrs. Brown, Boveri and Co., for an output of 500 kilowatts at 250 volts, when running at a speed of 2,100 R. P. M. A longitudinal and an end view of the machine are given, each view being in half-section. The commutator and the field magnet of this machine are referred to elsewhere. Here we are more concerned with the armature, the core plates of which are directly keyed on to the shaft to avoid any tendency to shift at the high speed at which the machine is run. Such shifting might throw the whole armature out of balance, and thus lead to serious trouble. The difficulty of ventilating an armature so built is met by piercing the core near the shaft with twelve longitudinal air-ducts, through which cool air is drawn, as will be described presently. In



Fig. 76.—Armature of Brown, Boveri 500 Kilowatt Turbo-Dynamo.

addition in the core length of 600 mm., there are no fewer than ten of the usual radial air-ducts. The laminations of the core are insulated from one another by thin paper pasted on the iron sheets before the core-plates are stamped out.

The shape of the slots for the windings can be seen in the cross-section, and it will be noticed that the outer ends of the teeth are so shaped as to provide the necessary supports for wooden wedges, with which the windings are held in their places, a method already described as being used in slow-speed machines. One of the great differences between all these turbo-dynamo armatures and the armatures of slow-speed machines, lies in the very carefully-designed arrangements which have to be made to keep the ends of the windings, including the end connections, in their places. The binding wires, straps, etc., used in the slow-speed machines are altogether too fragile to stand the strains to which they would be subjected at these high speeds. In their place, specially-designed *end caps* or bells are frequently used to prevent the displacement of the connectors by the centrifugal forces. These caps, obviously, cannot be made of magnetic material, and therefore iron or steel cannot be used. Instead, special alloys of great tensile strength are employed, and the material is disposed so as to be most effectively used. Some of the details of these end caps and their method of attachment to the revolving armature can be made out from Plate IV., and further information will be obtained from an inspection of Fig. 76, which is reproduced from a photograph of an armature of a larger machine, designed for an output of 1,500 kilowatts at, however, the lower speed of 1,000 R. P. M.

To enable the ventilating arrangements to be followed a complete machine of this type is shown in Fig. 77. The machine illustrated is the one to which the armature of Fig. 76 belongs. It will be noticed both in Fig. 76 and in Plate IV., that the ends of the magnet frame, including the collecting rings, are completely enclosed. For ventilating purposes cool air is drawn into the machine through a chamber within the bed-plate, passing through ducts parallel to the shaft, whence it is drawn by the fan blades seen in Fig. 76, through the end connections which it keeps cool, and then through the core-plate longitudinal ducts to the radial ducts of the core. From these it is discharged against the faces of the field-magnet poles, and passes through the ventilating ducts in the field-magnet cores, being finally discharged through a chimney-shaped opening at the top of the case. In this way the machines are efficiently ventilated, and can stand a 25 per cent. overload for 1 hour without injurious heating. Also, as none of the cooling air passes over the commutator, no copper dust from the commutator can be drawn into the windings.

Another danger in these high-speed machines when wound for high voltages is that the potential difference between successive commutator

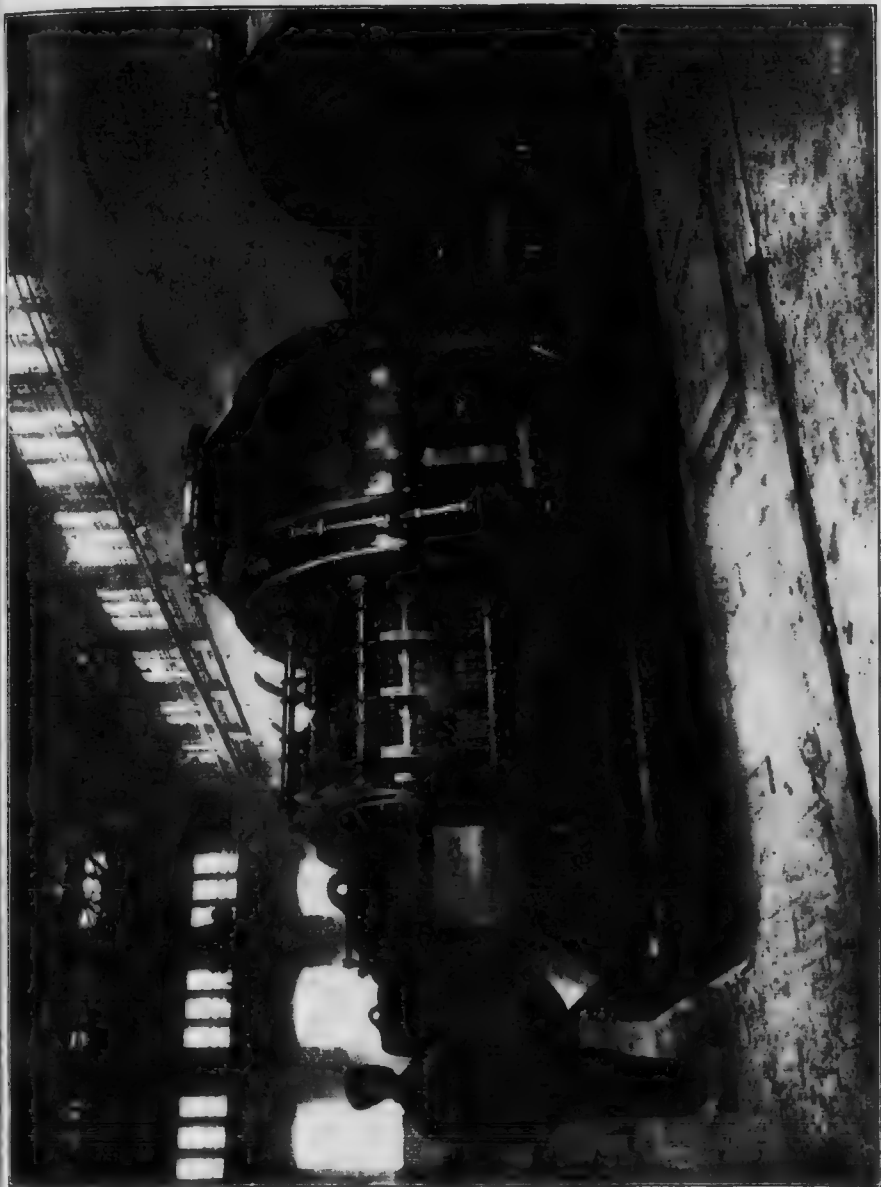


Fig. 77.—Brown, Boveri 1,000-Kilowatt 1,000 R. P. M. Turbo Dynamo.

segments, even when there is only one armature turn per segment, may be so high as to run the risk of an arc across the face of the mica insulation developing into a dangerous flash-over. The Westinghouse Company minimise this risk by introducing intermediate segments into the commutator connected to the middle of the winding, half-way across the armature.

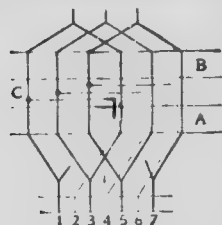


Fig. 78.—Diagram of Intermediate Tappings to Commutator.

The arrangement is shown diagrammatically in Fig. 78, which is not drawn to scale. Between the laminated core-plates assembled in the sections A and B of the armature there is a space *c* sufficiently wide to allow tappings to be carried down and brought along the axle to the additional commutator segments. These tappings are of small cross-section, not being intended to carry the full-load currents, and electrically the potential of the segment connected to a tapping is not half-way between the potentials of adjacent segments. It is

also claimed for this method that it facilitates commutation without interfering with ventilation and cooling.

Double-Current Armatures.—It has been shown in Chapter XIV. Volume I. (see pages 548 to 552) that ordinary continuous current armatures can be utilised for the production of alternate currents of any number of phases, the only addition required being the necessary collecting gear. Hence it follows that if, in addition to the commutator, the requisite number of slip rings, connected to the proper points in the armature winding, be provided, the one machine may supply at the same time



Fig. 79.—Double-Current Armature.

both continuous and alternate currents, the latter of any number of phases. The same possibility has also been referred to in Chapter XVII. of Volume I. (see page 636), when dealing with rotary converters. What is of interest here is that in actual practice the necessity sometimes arises, and *double-current machines*, as they are called, are built for carrying out the idea.

An armature of such a machine as built by the Brush Electrical



Fig. 80.—Armature Winding at Messrs. Mather and Platt's Works.

Engineering Co. is shown in Fig. 79. The fact that the output of the machine is 750 kilowatts, shows that there is a demand for large machines of this type.

The armature shown will give a continuous current of 1,500 amperes at 500 volts at its commutator. The axle carries also three slip rings connected to points 120 electrical degrees apart on the windings. These rings will therefore supply three-phase currents at about 360 volts up to the full current-carrying capacity of the machine, at the periodicity corresponding to its speed and number of poles.

The machine is essentially a rotary converter, with the A. C. rings alongside the commutator, instead of, as is more usual, being on the other side of the armature. As this is, however, a mere matter of convenience, and the subject of rotary converters is dealt with elsewhere, we do not propose to give any further examples of double-current machines here.

Winding Operations.—As an interesting conclusion to this section on close-coil armature winding, Fig. 80, gives a view of a bay of the winding shop at Messrs. Mather and Platt's works at Manchester. The reader can there see various winding processes in different stages, including, *inter alia*, the making of the "former" coils and their assembly on a partly-wound armature. The picture also gives some idea of the conditions under which such work is carried on in practice in a modern and up-to-date works.

Open-Coil Armatures.—The features which distinguish these from the ring- and drum-wound armatures have already been alluded to on page 469, Vol. I., and illustrated by the description of the well-known Brush arc-light machine. Another open-coil arc-light machine which has played an important part in the development of the dynamo is the equally well-known Thomson-Houston machine, which had several interesting ingenious devices for attaining the special objects in view. Partly, however, by the evolution for central station work of much larger machines than could be conveniently built in this form, and for other reasons it has been quite superseded by the more modern machines we are describing elsewhere. Readers who are interested in the historical development of the subject will be repaid by reference to the full details of this machine given in the last edition.

Disc Armatures.—Flat coils, arranged on the periphery of a wheel with their axes parallel to the axis of the wheel, have been successfully used for alternators—e.g. the Siemens (Fig. 535, Vol. I.) and the Ferranti (Fig. 537, Vol. I.), machines already described. Such a method of winding may be appropriately described as a disc winding, but as applied in the examples cited it is not available for the production of continuous currents on account of difficulties of commutation. Theoretically, however, the essential condition of the method is that the radial components of the coils are the active parts of the conductors, and by taking these separately and properly joining their extremities to one another and to a commutator

it has been found possible to build armatures of the "disc" or "wheel" type, in which the conductors revolve in a multipolar field similar to that of the alternators referred to. Faraday's original dynamo (Figs. 450 and 451, Vol. I.) was of this type, and had the further advantage of dispensing with a commutator.

Many attempts have been made to design disc machines which should satisfy the requirements of engineering practice, but only with a modified measure of success. In the majority of cases it

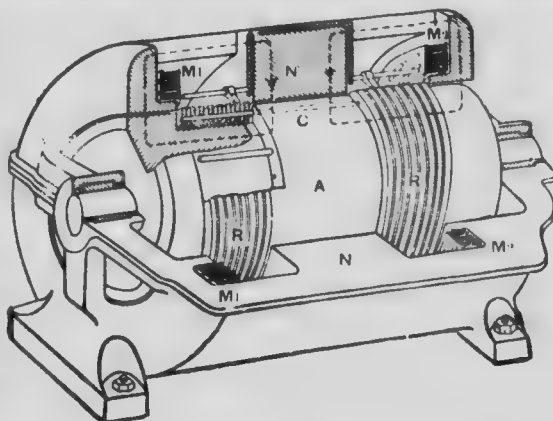


Fig. 81.—The Principle of a Homopolar Dynamo.

has not been found possible to dispense with the commutator and replace it by the sliding contacts of Faraday's disc dynamo. A fairly modern example, *Fritsche's Disc Dynamo*, was fully described in the last edition of

this work. The machine was an eight-pole machine with an armature 54 inches in diameter, having iron bars as nearly radial conductors. It had an output of 425 amperes at 115 volts when running at the low speed of 140 R. P. M., and similar machines have been built with outputs up to 800 kilowatts at similar voltages and even lower speeds.

Machines of this type, designed by Desroziers and built by Ereguet, were largely used in France.

In these machines the conductors were radial, and an ordinary commutator was employed; some of the difficulties of connecting the ends of the radial conductors were most ingeniously overcome by building the armature as two discs, which were

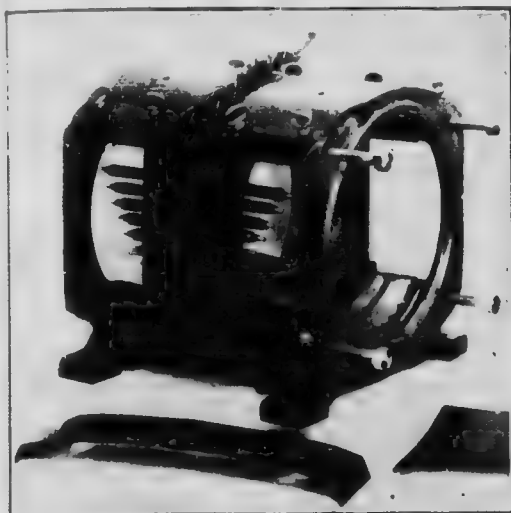


Fig. 82—Magnet Frame, showing the Stationary Conductors.

ductors were radial, and an ordinary commutator was employed; some of the difficulties of connecting the ends of the radial conductors were most ingeniously overcome by building the armature as two discs, which were

afterwards brought together with the ends of the conductors which require to be joined exactly opposite one another.

The weight efficiency of disc dynamos is high when compared with equivalent machines of other types. For instance, large disc machines have been built which have an output of one kilowatt per 73 lb. of weight or 13.5 watts per lb.

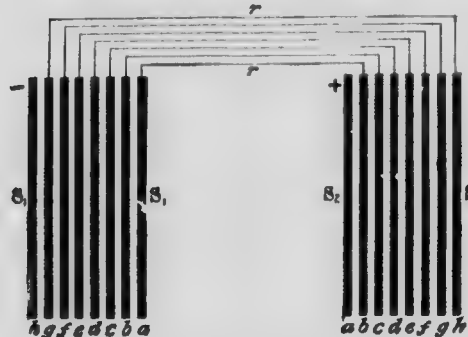


Fig. 83.—Stationary Connections of Slip Rings in Homopolar Dynamos.

Homopolar or Acyclic Dynamos.—The principle used in the Faraday disc dynamo which enables it to dispense with a commutator is that the active conductors are always cutting the magnetic lines of force of the field in the same

direction, and, therefore, there is in the conductors no reversal of E. M. F. to be made unidirectional by commutator action. As remarked above, attempts to secure this condition with radial conductors, as in the Faraday disc, have not been conspicuously successful. Better success has however been attained with conductors placed parallel to the axle on the surface of a cylinder or drum and made to pass continuously through a radial and unidirectional magnetic field.

The first practical difficulty met with in designing such machines is the low voltage per conductor attainable. The fundamental equation for the E. M. F. of each conductor is

$$E = (v l B) \div 10^8$$

where v is the velocity of the conductor in centimetres per second, l is the length of the conductor actual cutting lines of force and B is the field flux in gauss (lines per square centimetre). An easy calculation with average practical values for v , l and B will show that at the most a few volts only can be developed, and that therefore to build up a voltage of the magnitude ordinarily used in engineering work, some method must be devised to put the separate conductors in series without the connectors cutting lines of force in the wrong direction. The most

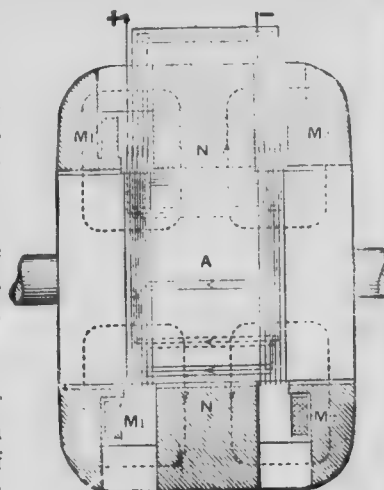


Fig. 84.—Section of a Homopolar Dynamo.

tical solution hitherto attained has been by using stationary connectors connecting slip rings attached to the ends of the rotating and the conductors. If, however, only low voltages, such as are used in electroplating work, are required, such series connectors may be dispensed with.

The general design adopted by Kennedy, Noegath, Feldman and others, is shown in Fig. 81, which is an isometric projection of a machine partly in section and with a portion of the field frame removed; the actual magnet frame of such a machine, showing some of the stationary connectors, is depicted in Fig. 82, which is from a photograph of an actual machine. The active conductors, one of which is

shown by dotted lines at *c* (Fig. 81) are arranged round the periphery of the armature core *A*, which in these machines need not be laminated. The ends of the conductors are attached to slip rings *R R* which are also carried by the core or rotor outside the limits of the annular magnet

Fig. 85.—Barbour's Homopolar Dynamo.

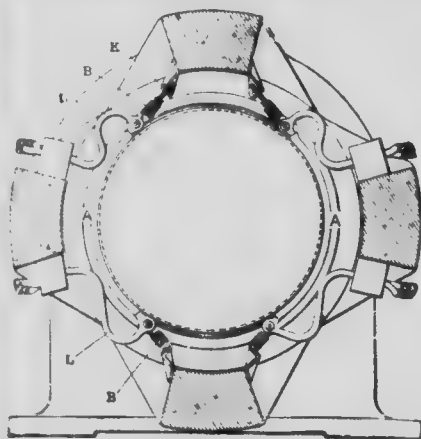
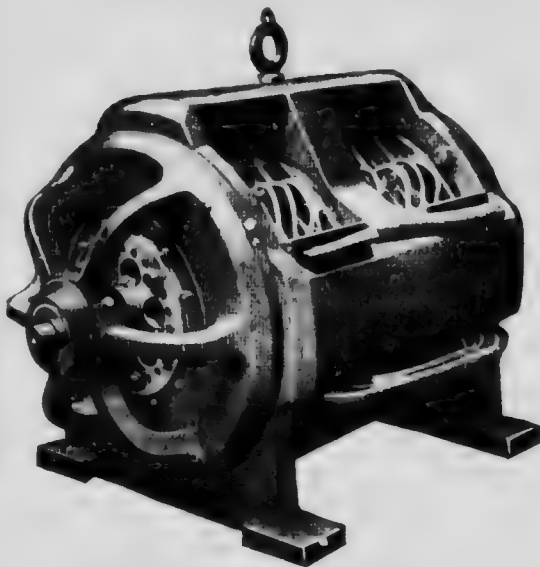


Fig. 86. Brushes on Barbour's Homopolar Dynamo.

pole *N N*. In Fig. 81 eight slip rings are shown at each end of the space occupied by the active conductors. For clearness these slip rings are shown separately and diagrammatically in Fig. 83, where the eight black bands *s₁ s₁* and *s₂ s₂* on either side represent the slip rings of Fig. 81, and the fine lines *r r* represent the fixed conductors of Fig. 82. The rings are marked from *a* to *h* outwards from the central space and each active conductor on the armature has its ends attached to one pair of rings similarly lettered. The fixed conductors *r r*

are attached to consecutive rings on either side. Thus ring *a* on the left is connected to ring *b* on the right, ring *b* on the left to ring *c* on the right, and so on. The final result is that the conductors grouped in parallel on each pair of rings have these groups joined in series, and that the ring *a* on the right and ring *b* on the left will be the terminals, $+$ and $-$, of the system.

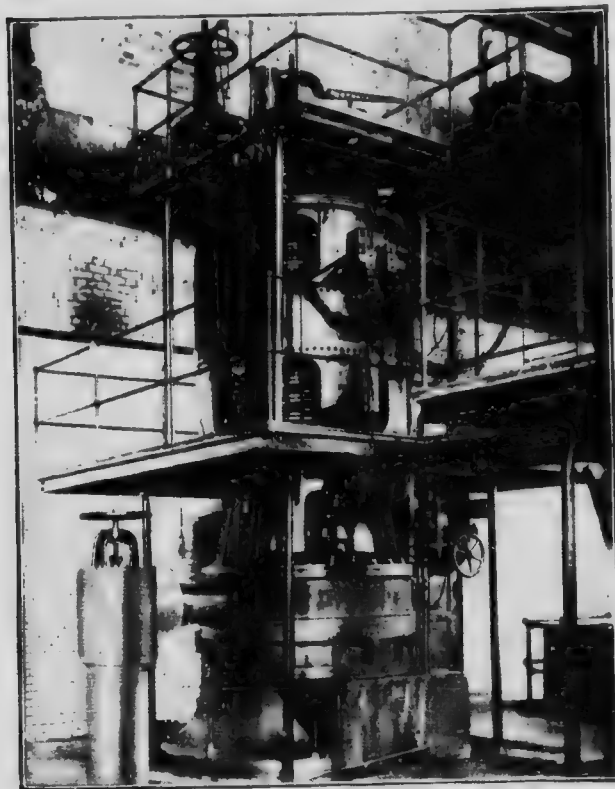


Fig. 87.—General Electric Company's Homopolar Turbo-Dynamo, 500 Kilowatts, 50 to 600 Volts, at 2,000 R. P. M.

continuous annular pole NN from which a magnetic flux flows radially inwards. The magnetic circuit is completed through the iron of the rotor axially outwards beneath the slip rings on either side, then radially outwards through the idle air gaps at either end, and through the connecting yokes of the outer frame which are pierced with large openings to give access to the brushes and slip rings (see Fig. 82).

A modern example of a homopolar generator, with modifications in mechanical details, is shown in Fig. 85, which is reproduced from a

A section, taken from Noeggerath's paper (1905), of a similar machine is given in Fig. 84, in which both some of the armature conductors and the fixed or frame conductors can be traced. A comparison of Figs. 81 and 84 will also make clear the details of the magnetic circuit. In both the exciting coils M_1M_1 and M_2M_2 are wound concentrically with the shaft, and each sets up fluxes whose general direction is shown by the closed dotted lines. The cylindric core *A* of the rotor is surrounded by a con-

photograph of a machine exhibited at Olympia (London) in September, 1911. This machine was designed by Mr. R. H. Barbour, managing director of Messrs. Homopolar Machines. It is intended to be driven by a steam turbine at 3,500 R. P. M., but was belt-driven at this speed at the exhibition, giving an output of 500 amperes at 100 volts or 50 kilowatts. The overall dimensions are $20\frac{1}{2}$ inches by 28 inches by $28\frac{1}{2}$ inches high, and the peripheral velocity is 12,800 feet or over 2 miles per minute. There are twelve conductors in tunnels in the armature iron, and the axial length of the centre pole which fixes the active length of the armature conductors is 6 inches. The slip rings, twelve at each end, are $\frac{1}{2}$ inch in diameter and are grooved. In the grooves lie the brushes A A Fig. 86, which are made of a flexible copper core with spiral armouring, and embrace a considerable fraction of the periphery of each ring. It is claimed that this form of brush so mounted makes better contact with the slip ring than the more common forms. These long flexible brushes are held in place round their slip rings by springs B B, the tension of which can be regulated by nuts and screws K K, the current being led away to the stationary frame conductors by flexibles L L.



Fig. 88.—Casting for Magnet Frame of 500-Kilowatt Homopolar Turbo-Dynamo.

A number of homopolar dynamos of a wide range of output have been built by the General Electric Company of America. One of these, for an output of 500 kilowatts, is shown in Fig. 87. It is driven at 2,000 R. P. M. by a Curtis vertical shaft steam turbine, and can be connected up to give the above output at pressures ranging from 50 to 600 volts. One of the magnet castings for the frame of the machine is shown separately in Fig. 88.

Many additional problems arise in the design of these machines, which considerations of space do not allow us to dwell upon in detail. Amongst these may be mentioned the collection of heavy currents from surfaces moving at speeds of four or more miles per minute, and the high centrifugal stresses incident to such speeds. The armature reactions due to the currents in the active conductors, the rings, and the frame conductors must not be overlooked. The new problems have been for the most part successfully solved, whilst some of the problems which give trouble in commutation machines are absent. The reader who desires to pursue the matter farther

will find an interesting article by Prof. Feldmann in *The Electrician* of 21st August, 1908, from which some of the above figures have been taken.

VI.—ARMATURE REACTIONS AND SPARKLESS RUNNING

In the preceding volume, on pages 502 to 505, we have shown how the existence of a current in the armature produces a reaction on the working field of a generator because its magnetic effect is superposed upon the magnetic effect due to the exciting coils. The general result is that the latter field is twisted in the direction of the rotation of the armature, being weakened under the leading pole tips *a, c*, Fig. 479, Vol. I., and strengthened under the trailing pole tips. It was also shown that, when the brushes have a forward lead, the conductors round the periphery of a closed coil armature can be divided into two groups (see Figs. 481 and 482, Vol. I.), one of which has a magnetising effect directly opposed to the magnetising effect of the exciting coils, and this group is therefore appropriately called the *demagnetising* group. The other group is equivalent to a solenoid whose core is perpendicular to the flux of the field magnets, and therefore it may well be referred to as the *cross-magnetising* group. In considering in more detail the effects of the magnetic reactions of the armature, it will be convenient to deal separately with these two groups.

The Demagnetising Reaction.—This effect depends upon the number of conductors in the demagnetising belt and the current in each conductor, in other words, upon the *demagnetising ampere-turns*. The width of the demagnetising belt, and therefore the number of conductors in it, varies directly with the *angle of lead*, which, as we have already seen, depends upon the relative strengths of the field magnet and the armature magnet, and in most machines increases with the load. The current in the armature conductors also increases with the load, and therefore, if the demagnetising ampere-turns of the maximum lead of the brushes be great, the reaction will increase more rapidly than the load. Hence the advantage of a design in which the fluctuation of lead from no load to full load is small.

The effect of the demagnetising belt is to weaken the effective field as the load increases, and therefore to diminish the E. M. F. of the machine. This will in its turn lower the P. D. at the brushes, which at the same time is being still further reduced by the increase in the lost volts (see page 514, Vol. I.). The double effect may be very serious, and therefore in practice a remedy is absolutely necessary. Where interpoles are not used, two methods are largely employed—namely, compound winding and chord winding.

(a) *Compound Winding.*—This has been briefly explained on page 6. The principal excitation being supplied by a shunt winding, additional turns of thick wire are added, which are traversed by the armature or the load current (see page 6) so as to add to the effect of the ampere-turns of the shunt winding. The ampere-turns of these additional coils will increase

proportionately, or nearly so, with the load, and by properly adjusting the number of turns the fall of the P. D., due both to the weakening of the field by the magnetic reaction and to the volts lost through ohmic resistance, can be almost exactly counteracted at all loads. We shall return to this general point when considering regulating devices (see page 177); at present we are concerned chiefly with the demagnetising effect.

The demagnetising ampere-turns can be calculated easily if the angle subtended (λ) be known, for the whole angle covered by the demagnetising conductors is 4λ , which is the fraction $\frac{4\lambda}{2\pi}$ of the whole circumference.

Therefore

$$\text{the demagnetising conductors} = z \times \frac{4\lambda}{2\pi},$$

$$\text{the demagnetising current} = \frac{1}{2} C_a \text{ (in bipolar machines),}$$

$$\begin{aligned} \text{the demagnetising ampere-turns} &= \frac{1}{2} C_a \times \frac{1}{2} z \times \frac{4\lambda}{2\pi} \\ &= \frac{C_a z \lambda}{2\pi} = 0.26 C_a z \lambda. \end{aligned}$$

If, therefore, the series coils be traversed by the whole armature current, the number of turns to be wound on the field magnets to counterbalance this particular reaction would appear to be $0.26 z \lambda$. But it must be remembered that, because of magnetic leakage, all the lines passing through the demagnetising solenoids do not pass through the armature, and therefore additional turns must be added to supply the leakage lines. These can be readily calculated when the coefficient of leakage (see page 47) is known. Practical methods of applying the series coils have already been described and illustrated (see Figs. 21 and 25).

Chord Winding.—The demagnetising effect in a drum armature can also be not only counteracted, but practically abolished, by modifying the winding scheme. Referring to Fig. 46, if, instead of connecting the ends of conductors nearly diametrically opposite one another, we connect No. 1 across the front to No. 20, which is at an angular distance from it of about the polar span, we have what is known as *chord winding*. No. 20 is then connected across the back to No. 3, which in its turn is connected across the front to No. 22, and so on. The winding table for this system of connections would be as follows:—

B	F	B	F	B	F	B	F	B
U	D	U	D	U	D	U	D	
1	20	3	22	5	24	7	26	
9	28	11	30	13	32	15	34	
17	36	19	38	21	40	23	42	
25	44	27	46	29	48	31	2	
33	4	35	6	37	8	39	10	
41	12	43	14	45	16	47	18	

Some of the connections for this system, more especially for the conductors in the polar gaps which are supposed to be at the top and bottom of the figure, are shown diagrammatically in Fig. 89, in which the heavy lines represent the connections at the front or commutator end, and the dotted lines those at the back end of the armature. The positions on the former marked with a black dot on the inner circle are the places to be connected to the commutator segments. In order to show currents in all the conductors only one commutator bar is supposed to be under each brush, the bar joined to the 3—22 cross-connection being under the $\perp$ brush, and the bar under the 27—46 connection being under the — brush. On tracing the course of the current in the neighbourhood of the brushes it will be found that, in the polar gap at the top, conductors 47, 1, and 3 have forward currents, whilst conductors 46, 48, and 2 have backward currents. For clearness the conductors carrying the forward currents are shown white and those carrying the backward currents are shaded. As the currents are of the same magnitude in

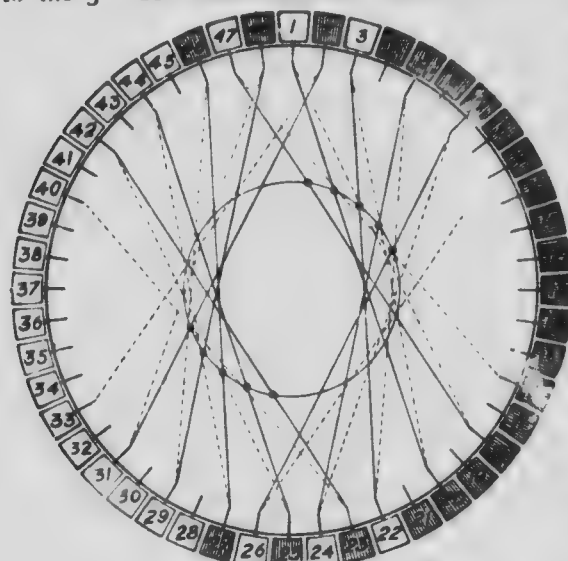


Fig. 89.—Diagram of Chord Winding.

each conductor, the magnetic effect of the first group cancels the magnetic effect of the second, and therefore these six conductors, which are the ones in the ordinary demagnetising belt, have no magnetic effect. The same may be said of the six conductors at the bottom polar gap, and thus on the whole the demagnetising effect is eliminated.

The process of applying a chord winding to an actual armature is shown in Fig. 90, which represents a partially wound armature of one of Messrs. Bruce Peebles and Co.'s dynamos intended to give 65 amperes at 230 volts when running at 250 R. P. M. in a four-pole field. The conductor used is round wire, which is cut off into exact lengths and formed into the required shape *in situ* on the armature core. There are several turns of wire per pole, and all the sections are connected in series at the commutator bars, which the only joints in the winding occur. This

Method of winding the armature is only used when it is necessary to have several layers of conductors, and where "former" coils or bar winding would be unmechanical.

It may be well to point out here that an additional advantage of chord winding is that the end connectors are appreciably shorter than in the neutral winding previously described; consequently, the idle resistance is reduced. On the other hand, there must be some loss of E. M. F., the currents in the conductors 46, 48, 2, 22, 24 and 26 are opposed to the induced E. M. F.'s. These induced E. M. F.'s, however, are generated by the fringe of the field outside the pole tips, and therefore with well-designed machines they should be almost negligible.



Fig. 90.—Chord Winding of a Bruce Peebles Armature.

The Cross-Magnetising Reactions and Commutation.—The chief effect of these on the flux due to the field-magnet coils is to weaken the field under the leading and strengthen it under the trailing pole tips. This may very seriously affect the sparkless running of the machine.

We have already (see page 504, Vol. I.) shown that the brushes must be advanced in the direction of rotation if the commutating section during the act of commutation is to be in what is known as the neutral position—that is, that position in which for the moment the flux through the section is not changing, and in which, therefore, there will be no induced E. M. F. in the section. A little consideration, however, will show that this does not fulfil all the conditions, for when a coil is coming up to the brush it is carrying its full share of the armature current, and whilst still carrying this current it is short-circuited by the brush. The current immediately begins to die away, and it has not only to die away to zero, but, if the section is to

be electrically ready to swing into the armature circuit on the other side as it passes from under the brush, it should have set up in it whilst still short-circuited a current practically equal to the current which it will be called upon to carry when it is quite clear of the brush. If this condition be not satisfied, there will be a more or less vicious spark when the short circuit is broken. For, if there be no, or too little, current in the section, its inductance will be sufficiently high to add an appreciable impedance to the main circuit, and as the tip of the brush slips across the insulating gap there will be a spark due to the sudden change of current. If, on the other hand, the current in the short-circuited section be too great, there

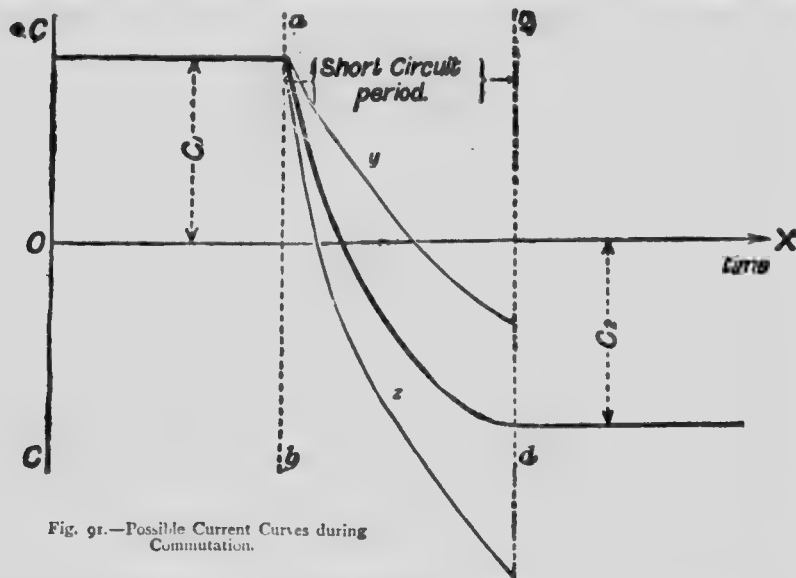


Fig. 91.—Possible Current Curves during Commutation.

will be a spark due to the sudden reduction of this current to the normal value.

It is therefore necessary that before the short circuit is removed the section should be cutting lines of force in the new field, so that the requisite E. M. F. may be obtained to generate the necessary current. In fact, the current curves just before, during, and after the short circuit should be something like that shown at x in Fig. 91, though the exact form between the vertical lines ab and cd may be almost infinitely varied, provided it never rises above the value c_1 on the $+$ side or sinks below the equal value c_2 on the $-$ side. In actual practice there is reason to believe that this condition is often violated. The general shape of the curves, however, will be logarithmic, as in Fig. 91, and not sinusoidal, as is sometimes erroneously assumed. The ideal curve is shown in the thick line x . As the

short-circuit resistance is very low, only a small induced E. M. F. is required, and this can be obtained in a comparatively weak field of the right kind. But some *reversing field*, as it is called, is necessary, and therefore the brushes must be advanced beyond the neutral position if no other special device be adopted.

The *time* of short circuit is also an important element in the solution, for it is obvious that it should be such as to allow the ordinate of the particular logarithmic curve which represents the changes of the current to have the correct value, as nearly as possible, at the moment when the short circuit is removed. If the time be too short, as in the case of the curve *y* (Fig. 91), the reversed current will not have reached its full value before the short circuit is removed. On the other hand, if the time be too long the current during the short circuit as shown in curve *z* will have reached far too high a value, and the opening of the short circuit will give rise to serious sparking. It can be shown mathematically that if the time (*t*) of short circuit be about three times the *time constant* $\frac{L}{R}$ of the short-circuited coil, the reversed current will be equal to about 90 per cent. of the load current, whilst if *t* be about 7.5 times the time constant, the reversed current will be within nearly one per cent. of the correct value. The calculation assumes that a definite reversing E. M. F. is thrown into the short-circuited coil proportional to its resistance. The exact calculation of the resistance, which includes the contact resistance of the brushes, is not, however, a very easy matter.

Now, it may happen, if the cross-magnetising effect is great, that the flux due to it under the leading pole tip (*a*, Fig. 479, Vol. I.) entirely or nearly cancels the flux in the opposite direction due to the field magnet. When this happens the reversing field disappears and sparkless commutation is impossible for any position of the brushes. The magnetic flux due to the cross-magnetising belt depends upon the ampere-turns of the belt or the total flux of current in the conductors. Hence it is that we cannot increase the output of a dynamo at a given voltage merely by deepening the slots and providing heavier conductors to carry the increased current. Sooner or later, besides other complications, this will lead to a cross-magnetising flux, which will produce sparking on the commutator at all possible positions of the brushes.

The magnetic flux due to the cross-magnetising belt, however, depends not only on the ampere-turns or magneto-motive force of that belt, but also upon the magnetic reluctance of the path provided. Therefore a remedy for the evil effects referred to may be provided either (*a*) by introducing an opposing or counter M. M. F. (magneto-motive force) into this magnetic circuit, or (*b*) by increasing the reluctance of the circuit. In either case the cross-magnetic flux and its effects will be diminished. The

same object can also be attained by (c) special armature windings so placed in the active part of the field as to produce the necessary reversing E. M. F. in the section under commutation.

(a) *Counter M. M. F.* (i.) *Compensating Coils.*—To use the first method of balancing the cross-magnetising magneto-motive force by a counter M. M. F., a method advocated very many years ago by Dr. Thompson, Professor Forbes, and others, it is advisable to place the balancing or compensating coil in such a part of the magnetic circuit of the disturbing coil that it shall enclose all the magnetic flux due to the latter. The only possible place where this can be done effectually in a bipolar machine is for the compensating coil to surround the disturbing armature windings with a coil, having a vertical axis in the case shown in Fig. 481, Vol. I. Difficulties of construction render this position not easy to use, and therefore, for this purpose, Dr. Ryan and others many years ago made use of the spaces between the polar horns both above and below the armature.

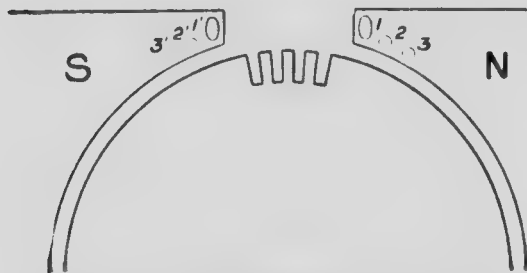


Fig. 92.—Positions of Ryan Balancing or Compensating Coils in Polar Gap.

which are bored in them parallel to the shaft. These coils being placed electrically in series with the armature, the current in them will rise and fall with the armature current which is the disturbing cause, and therefore theoretically by properly adjusting the number of turns, the other polar gap or gaps also being used, it should be possible to supply a sufficient number of balancing ampere-turns to compensate exactly for the disturbing ampere-turns on the armature.

A modern and somewhat remarkable instance of the use of compensating coils only to balance the armature reaction is given in the Parsons turbodynamo, to which reference has already been made (see page 87). A cross-section, showing the magnetic circuit of the machine, is given in Fig. 93. It is a four-pole machine, with salient poles, and with the magnetising coils well back from the armature, to make room for the polar extensions of the core, which are necessary to carry the compensating windings without unduly increasing the reluctance of the magnetic circuit. The slots which carry these windings are much deeper radially than the armature slots, so

Fig. 92 shows diagrammatically the arrangements for one gap. The compensating coils are threaded through the holes 1 1'; 2 2'; 3 3'; etc. In order to obtain the requisite support for the balancing coils, the polar horns are thickened and the coils threaded through the holes shown,

the compensating ampere-turns may be much greater than the armature ampere-turns, whose magnetic effect they are intended to neutralise.

It has been found in actual practice that if the ampere-turns on these compensating coils are two to two and a-half times the ampere-turns on the armature, the machine will run sparklessly with a 25 per cent. overload. The absence of the interpole diminishes the reactions of the compensating

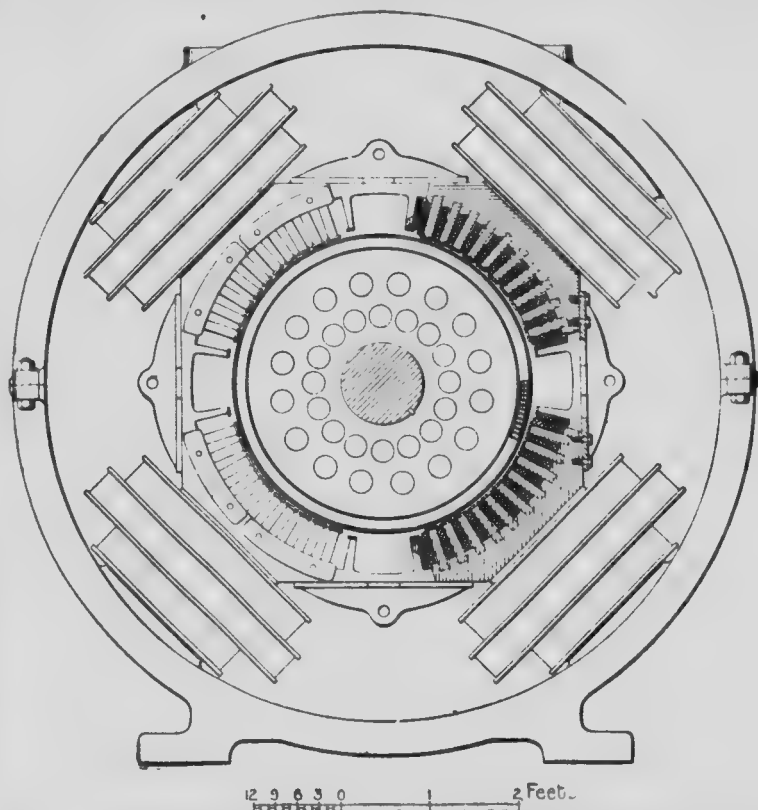


Fig. 93.—1,000-Kilowatt Parsons Turbo-Dynamo, with Compensating Windings in the Pole Faces.

coils when the load is suddenly changed. The machine gives 1,000 kilowatts at 500 volts at 1,200 R. P. M., and can co-operate without trouble with the turbine when the whole plant is called upon to face a sudden overload.

(ii.) *Interpoles.*—By a process similar to over-compounding on the field-magnet coils the turns on the compensating coils may be increased beyond the number necessary to balance the M. M. F. of the cross-magnetising belt, so that as the armature current grows the cross magnetising M. M. F. may be reversed and made to produce the necessary reversing field referred to

above: To assist this effect Dr. Ryan introduced an iron core into the balancing coil either by means of a cast-iron bridge across the pole tips, with a commutating lug and the necessary slots for the coils, or by a pole ring entirely encircling the armature and carrying the balancing coils in properly placed slots. The essential features of his methods have been revived in recent years in the form of *interpoles* which are now very widely used by most dynamo builders. Machines of this type have already been

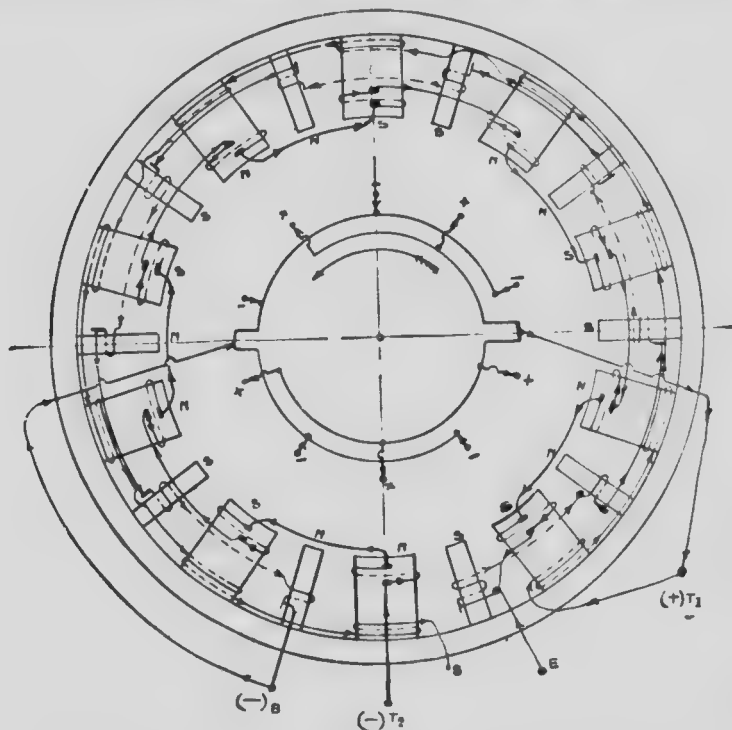


Fig. 94.—Diagram of Pole Ring of Mather and Platt 600-Kilowatt 10-Pole Dynamo.

referred to and illustrated in Figs. 7, 11, 12 and 15. A diagram of the pole ring of the ten-pole Mather and Platt dynamo of Plate II. is given in Fig. 94, in which also the windings of the shunt, the compounding and the commutating circuits are shown. The external terminals of the machine are at T_1 and T_2 , the former being the positive. The shunt excitation is nearest the yoke, and is shown by the windings from T_1 to s , which is connected to T_2 , the negative terminal, through a regulating resistance. The commutating winding on the interpoles and the compounding windings on the main magnets are in series between T_2 and the terminal of the —^w brush ring B and the load current therefore passes through these

windings on its way from the terminal T_2 to the —" brushes: A terminal is brought out where the two windings are linked up. This terminal is connected to an equalising main if two or more machines are being run in parallel. An inspection of Fig. 12 will show that the connections from one pole to the next are secured by removable bolts so they can be readily changed and a pole piece or its coils dismantled, in the event of a breakdown, without disturbing the rest of the magnet parts.

The machine is of 100 kilowatts, and runs smoothly with 50 per cent. overload; the temperature rise of the commutator after running six hours at full load is only $24^{\circ}\text{C}.$, and after two hours at 25 per cent. overload is only $15^{\circ}\text{C}.$

The connections of the circuits of a shunt-wound dynamo with series-wound interpoles are also well shown in Plate III., which gives many details of the 100-kilowatt Crompton dynamo of this type. Heavy cables, three in each case, carry the current between the positive and negative brush rings,

the blocks A and B, of which B acts as one of the external terminals, say the negative T_2 . From the positive block A the whole current of the machine is wound round the exciting coils of the ten interpoles to the block C, which is connected in its turn by short heavy cables to the block D on the magnet which acts as the positive terminal T_1 of the machine. The terminals

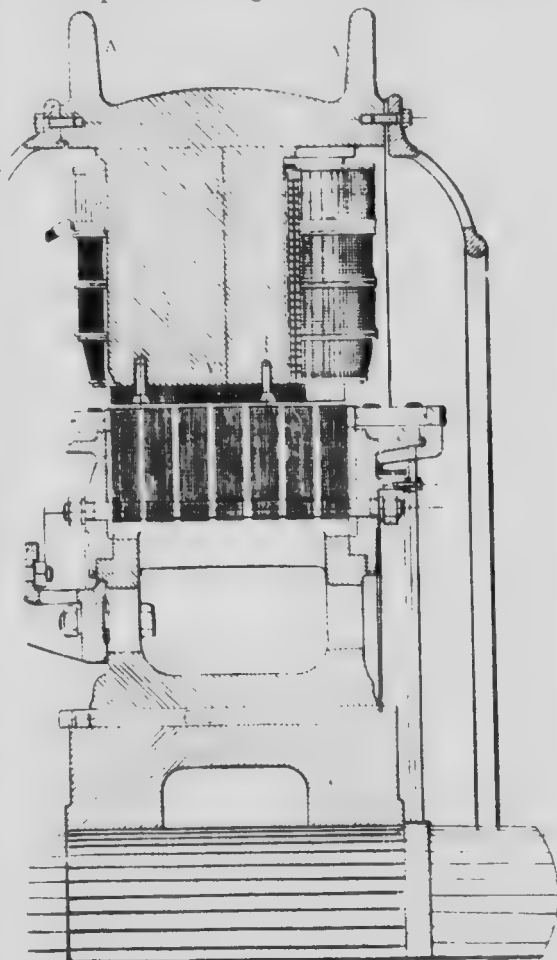


Fig. 95.—Section of 100-Kilowatt Slow Speed Dynamo, showing Main and Auxiliary Poles.

of the shunt circuit of the exciting coils on the main magnet poles are connected to small terminal blocks F and G, one of which is joined direct to the negative terminal T_2 , and the other through an adjustable resistance placed between a and b , to the positive terminal block T_1 .

Still fuller details of the poles and corresponding interpoles of a large machine are given in Figs. 95 and 96, which have been prepared from data supplied by the International Electrical Engineering Company of Liège, with reference to a machine designed for an output of 900 kilowatts at the low speed of 110 R. P. M. The dynamo has fourteen poles and fourteen interpoles, and gives 500 volts at no load, but is over-compounded so as to raise the terminal P. D. to 550 volts at full load. The internal diameter of the pole faces is 230 cm. (90.5 inches), and the external diameter of the yoke, exclusive of the flanges A A, is 360 cms. (142 inches); the shaft where it carries the armature spider is 52 cms. (20.2 inches) in diameter. These rough dimensions will give some idea of the size of the machine.

Two of the interpoles

lie on a horizontal diameter along which and through the pole cores the magnet system is divided into two halves which are bolted together.

This joint therefore crosses the main flux at right angles, but is in the line of the cross-magnetising flux. The axial section in Fig. 95 is ingeniously drawn to give the particulars of both a main pole and an auxiliary pole. On the left of the line XY the section shows half of one of the main or principal poles, the cross-section at right angles to XY of the complete pole being shown at A in Fig. 96. The pole core, as will be seen in Fig. 96, is, in cross-section, rectangular with semi-circular ends, being 485 mm. (19.1 inches) long and 275 mm. (10.8 inches) wide. On the right side of the line XY in Fig. 95 is shown, in section, half of one of the interpoles, the full cross-section of which, at right angles to XY , appears at B in Fig. 96.

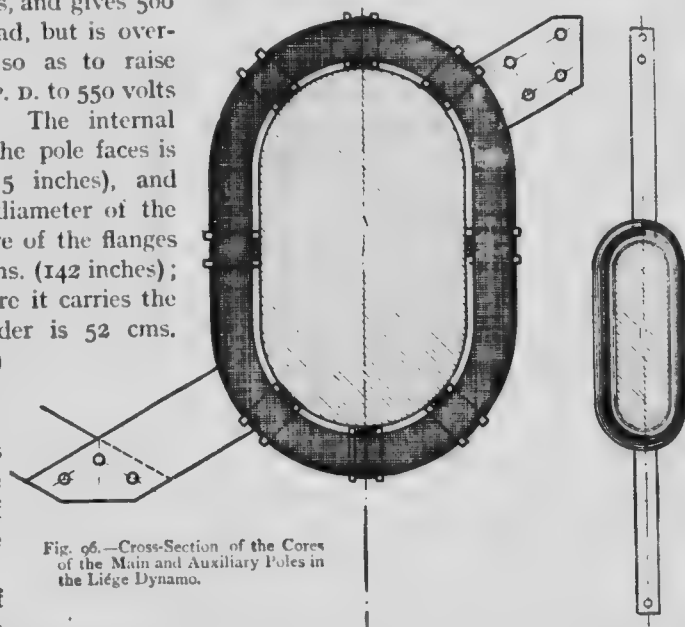


Fig. 96.—Cross-Section of the Cores of the Main and Auxiliary Poles in the Liège Dynamo.

This cross-section also is rectangular, with semi-circular ends ; it is 250 mm. (9.85 inches) long and 75 mm. (2.95 inches) wide. The sections A and B are in correct alignment, except laterally ; the bottom of the diagram is towards the commutator end of the machine and the front edge of each core lies in the same vertical plane. The interpole is, therefore at the commutator end, and only covers about half the length of the armature core. Both cores project inwards from the yoke ring and are provided with laminated pole faces about 35 mm. thick, screwed on as shown. The distance from the yoke ring to the pole face is 50 cms. (19.7 inches), and provides ample winding space for the coils, both series and shunt. The windings are separated from the core by distance pieces (A, Fig. 96), leaving ample space for cool air to pass through and carry away the heat generated, the air being set in motion by being driven outwards through the wide ducts of the revolving armature, acquiring thereby a radial velocity which will tend to carry some of it through the space referred to. The windings of the interpoles appear to be in two layers (Fig. 96), and closer to the cores ; they, of course, carry the load current.

There are other interesting details in Fig. 95, but as corresponding details in other machines have been fully explained elsewhere, the reader will find it interesting to examine the drawing carefully without further explanation here.

Turbo-Dynamos.—As remarked later (see p. 114), it is usually found necessary in dealing with the commutation and armature reactions on turbo-dynamos to employ both compensating polar windings and interpoles. This is notably the case in the higher-speed machines of large output, the wound field frame of one of which is shown in Fig. 97. The machine of which this forms a part is a Westinghouse four-pole 800-kilowatt turbo-dynamo, and both the compensating windings and the interpoles are very clearly illustrated in the figure. The pole shoe, which is built up of laminated iron, is perforated for the compensating windings throughout its whole extent, and not merely at the tips, as shown diagrammatically in Fig. 92. The carcass of a much smaller, but somewhat similar machine constructed by Messrs. Brown, Boveri and Co. has already been depicted in Fig. 8. In the Westinghouse machine (Fig. 97) there are no fewer than sixteen slots or tunnels in each pole for these windings, these tunnels being grouped half and half with the corresponding tunnels in adjacent poles to receive the windings. The problem of connecting the conductors in corresponding slots requires careful attention in view of considerations of space, and the forces which may be called into play when in use, especially if a short circuit should occur. In Fig. 97 one half the conductors (four in each group) come out straight, and heavy segmental straps *aa* are used for connectors, whilst the other four, those nearest the pole tips, are joined up by connectors

bent outwards towards the yoke, as can be seen at *b*. The windings for the interpoles, the coil of which can be made out on the right-hand bottom core, do not present similar difficulties, whilst the main exciting coils *m m* lie back against the yoke in their usual positions on the main projecting cores.

As a further example, Fig. 98 depicts the wound field magnet of one of Messrs. Brown, Boveri and Co.'s turbo-dynamos. The machine is bipolar, and has an output of 135 kilowatts. It is interesting to compare



Fig. 97.—Field Winding of Westinghouse Four-Pole 800-Kilowatt Turbo-Dynamo.

the devices used in this case to secure the end connections of the main field and compensating coils with those used in Fig. 97. In Fig. 98 there appear to be thirteen slots in each pole face for the compensating windings, and each slot contains two windings. There are, therefore, thirteen connections to be brought over from left to right for each set of windings, and these connections are neatly arranged back against the sides of the core plates, being firmly held in place by proper cleats. The main field being horizontal the connections for its windings are vertical, and they can be plainly seen on the right- and left-hand sides of the figure where, on the horizontal diameter, they are very securely anchored to the frame. There appears to be no separate winding for the two interpoles, which lie on the vertical diameter, but these interpoles are, of course, excited by the compensating windings, and thus assist the commutation in the manner already explained.

With the compensating coils so widely distributed, the distortion of the field due to armature reaction is very effectively prevented, whilst

the devices used in this case to secure the end connections of the main field and compensating coils with those used in Fig. 97. In Fig. 98 there appear to be thirteen slots in each pole face for the compensating windings, and each slot contains two windings. There are, therefore, thirteen connections to be brought over from left to right for each set of windings, and these connections

the presence of the interpolar projections, with or without windings, concentrates on the neutral zone a reversing field which ensures excellent commutation. Both sets of coils act primarily by introducing a counter M. F. into the cross-magnetic circuit of the armature, and both devices require higher excitation necessary on the main coils. This is due, as regards the compensating coils, to the increased reluctance of the main magnetic circuit caused by the removal of so much useful iron along the whole face of the poles, though, per contra, the reluctance of the cross-magnetic circuit is still more seriously increased. The interpole in its turn acts as a shunt to the main magnetic circuit, and therefore a somewhat higher excitation is required to provide the necessary useful flux through the armature.

It is worth noting that the whole field system of Fig. 97 is divided horizontally, the two halves being bolted together, and that the dividing plane passes through the mid-section of two of the main magnet cores. In these cores therefore, the reluctance of the joint is of no consequence, as its plane lies parallel to and not across the magnetic flux.

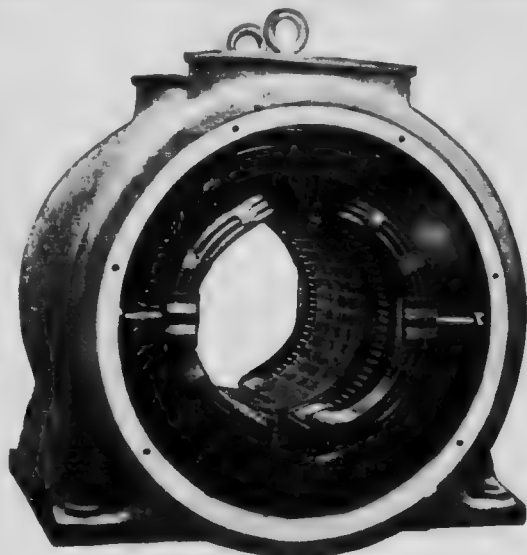


Fig. 98.—Field Winding of Brown, Boveri Bipolar 135-Kilowatt Turbo-Dynamo.

Finally, further particulars are given in Fig. 99 of the salient pole type of turbo-dynamo field magnet, built by the Brush Electrical Engineering Company, which has already been briefly referred to on page 14 (Fig. 7). Fig. 99 is a longitudinal section of the machine, and gives details of the main poles and interpoles, the former in the upper half of the figure, and the latter in the lower half. Of course, these poles are diametrically opposite one another, but it is convenient and instructive to show them in the same drawing. Note should be taken of the very simple type of pole shoe attached to the interpoles as compared with the elaborately designed and laminated pole shoe on the main poles, these pole shoes being held together by rings. The slots in the latter, of which there are sixteen in each pole face, carry the compensating winding referred to above. It should further be noted that the actual winding on the

interpoles is confined to a comparatively short depth of the core immediately behind the pole shoe, the rest of the core being covered with a wooden sleeve. The interpole excitation is, therefore, approximately the same cylindric belt as that of the compensating coils. Attention may also be drawn to the numerous and wide ventilating ducts in the armature

which discharge cooling air against the pole shoes and the compensating windings.

Excitation of Turbo-Dynamos.—It will be gathered from the foregoing that in many turbo-dynamos, more especially those which present a smooth cylindric surface to the revolving armature, there are three sets of windings to be provided for on the stationary field-magnets. These are (i.) the main field shunt windings, (ii.) the compensating and interpole series windings, and (iii.) the compound series winding. The winding scheme has therefore to be almost as carefully worked out as the winding scheme for the armature.



Fig. 99.—Section of Field Magnet of Brush 750-Kilowatt Turbo-Dynamo.

The scheme of winding used by Messrs. Brown, Boveri and Co. for four-pole machines similar to that whose carcass is illustrated in Fig. 8 is shown in Fig. 100, which is a diagram of the radial type (see page 69) applied in this case, not to an armature, but to a field-magnet winding. The narrow slots are represented diagrammatically by the little circles s_1, s_1 , and the wider slots by the rectangles s_2, s_2 with circular ends. The *main-excitation*, a shunt winding, is indicated by the double-line sectors M_1, M_2 , which also on their inner arcs M_1 give the positions of the four main

les. The terminal connections for this winding and the inter-connections are not shown. The *compensation windings* are shown by the continuous line which, starting from the terminal T_1 , can be traced through the diagram to the terminal T_2 . It will be found that this winding is in four chief sections symmetrical as regards the interpoles p_1 , p_2 , p_3 , and p_4 . Each chief section consists of two series of nine bars; one series in which the bars, shown by long radial lines project straight out at both ends to meet the circular connectors K_1 , K_2 , and the other series, in which the nine bars, shown by

short radial lines, are bent over at their ends so that the circular connectors K lie closer to the core and pass behind the projecting bars of the other series. Except at the interpoles, there is one bar of each kind in each slot, and 72 bars in all. Lastly, the *compounding winding* is shown by the dotted line NLM which lies between the terminals X and Y . There are only four bars in this winding, the

current through which gives a magnetic field coincident in position with that of the main field. This current is, of course a *series* current.

One of the results of the presence of a powerful compensating field, with its windings distributed all over the face of the poles of the main field, is that if the machine be run in parallel with other machines, there is a danger of the direction of its field being reversed. Should this happen, the machine would commence to run as a motor, and in a few seconds would attain a dangerous speed. To avoid this danger some manufacturers arrange to have the machines *separately excited* either from a suitable source of supply, or from a special exciter built upon the shaft. In Fig. 101 is shown a dynamo shaft of one of Brown, Boveri's turbo-dynamos with an

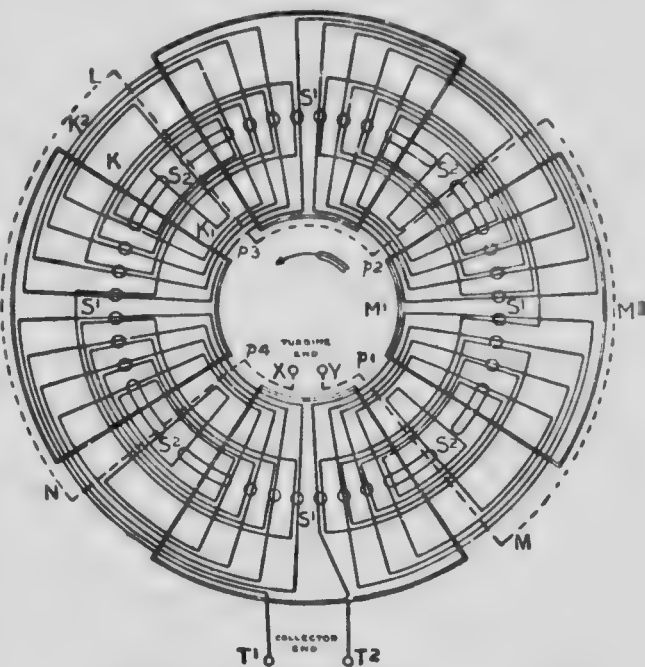


Fig. 100.—Diagram of Four-Pole Field Winding for a Turbo-Dynamo.

exciter armature on the commutator end. A complete machine with the exciter carried on a bracket on the end pedestal is illustrated later (Fig. 17).

(b) *Increased Reluctance.*—Since the cross-magnetising flux (see Fig. 47, Vol. I.) is at right angles to the field flux in the iron of the pole pieces, it is obviously possible to increase the reluctance of one path without seriously interfering with the reluctance of the other. Thus, as shown diagram-

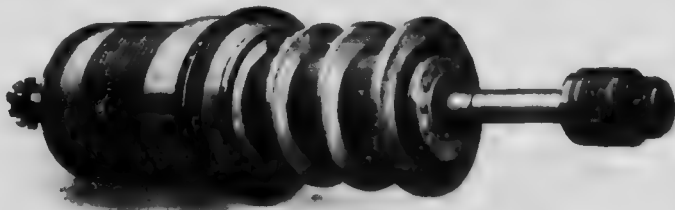


Fig. 101.—Main and Exciter Armatures on same Shaft of a Brown, Boveri Turbo-Dynamo.

matically in Fig. 102, a series of slots parallel to the shaft of the machine and in the direction of the main flux will have little effect on the latter, whilst they will lie across the cross-magnetising path and add considerably to its reluctance, with the result that the lines will be forced in greater numbers back across the working air gap into the armature iron before they reach the trailing pole horn. In addition, the total cross-flux will be

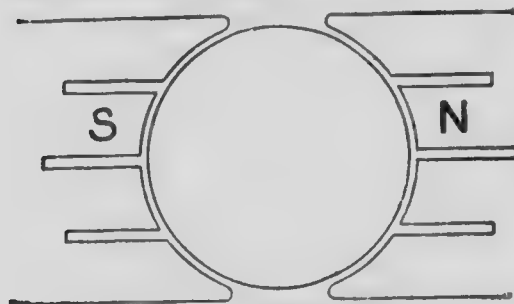


Fig. 102.—Increase of Cross-Magnetisation Reluctance.

reduced in proportion to the increase in the reluctance. Some makers are content with a single slot either in the middle of the pole face or near the leading horn, whilst in machines of the Manchester type (Fig. 400, Vol. I.) increased reluctance in the cross-magnetising path, besides a saving of material where it is not re-

quired for the main flux, is obtained by a deep V-shaped depression behind the pole piece. Such depressions, though scarcely deep enough for our present purpose, are shown in the multipolar field magnet of Figs. 38 and 39. It is obvious that the slots in the main pole faces of interpole machines, which have been fully described above, have the same magnetic effect as the much earlier designed unwound slots of Fig. 102.

Instead of, or in addition to, the increase of the total reluctance, it is possible to increase the reluctance locally at any particular part of the

at where the disturbing flux is specially prominent. Such places are especially (see Fig. 480, Vol. I.) at the trailing horns, and a favourite method is to shape these trailing horns specially so that whilst giving a good distribution at no load they are then nearly saturated. Therefore, when the magnetising flux comes on as the load increases, the high reluctance of these projections dams back, as it were, the flux from them and throws it back into the thick polar faces in direct line with the general flux. Another method is to increase the length of the air gap at the polar horn, thus increasing the reluctance there and turning back the cross flux to the more central regions.

These methods of dealing with the difficulties of commutation are of

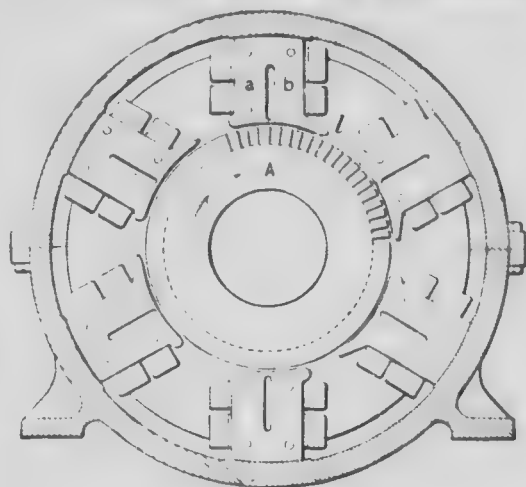


Fig. 103.

Sections of the Johnson-Lundell Dynamo.



Fig. 104.

of great interest, and are still used, notwithstanding the greater popularity of the interpole methods. Some examples from actual machines will make this clearer, and we give first, in Figs. 103 and 104, illustrations of the magnetic circuit of a Johnson-Lundell multipolar generator. Fig. 103 is a cross-section through the centre of the poles and at right angles to the axis, whilst Fig. 104 is a cross-section through the axis and the central cores. The cores and pole faces are built up from sheet-iron stampings of the shape shown in Fig. 103, these stampings being clamped together by the bolts as shown. The result is a core practically divided into two parts, *a* and *b*, by a deep slot parallel to the shaft of the machine. On a pole face with a slight projection beyond the line of the core on the leading horn, but, on the trailing horn, with a long projection *l* turned up slightly at the end so as to widen the air gap there. The quantity and

permeability of the iron used is such that at no-load there is a fairly uniform distribution under the pole face throughout the air gap, as shown by the line *c d e f* in Fig. 105, in which the flux densities are plotted vertically and the positions horizontally. At this stage, however, the flux density in the projecting lug *l* is on the flat part of the magnetisation curve (see Fig. 40), whilst the density in the core is fairly well down on the steep rising part. Consequently, when the load comes on and the cross-magnetising flux *c k l f* is added to the no-load flux, the result is the curve *c g h j*, in which, although the flux at the trailing horn is increased, there is very little effect on the flux at the leading horn. The positions of the extremities of the leading and trailing pole tips are marked by the points *A* and *B* respectively. The dip in the middle of the curve *c g h j* is due to the high reluctance of the central slot and its deflecting action on the flux. The general result is that the reversing field near the leading polar horns is

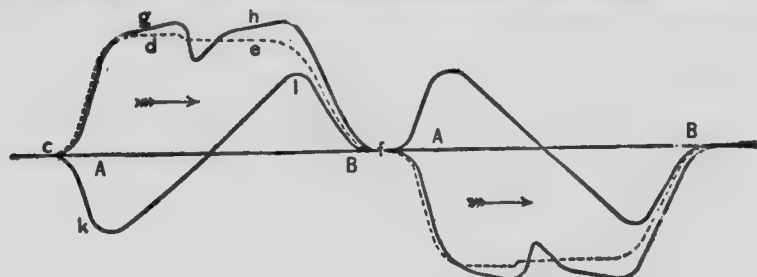


Fig. 105.—Flux Densities in the Air Gaps of Johnson-Lundell Dynamo.

not disturbed by increase of load, and therefore, when properly adjusted for reversal in the original design, the machine runs sparklessly at all loads with nearly fixed brushes. It is obvious, however, that a stronger reversing field is required at full load than at light loads, and that therefore for equally faultless running the lead must be slightly increased as the load increases. Fig. 106 gives a perspective view of the carcass of the field magnets of the machine, and shows some additional details of construction. A thin iron sheet appears to be slipped over the polar stampings covering up the wide central slot, and there are projecting lugs on the end plates to assist in holding the magnetising coils in position.

Very interesting applications of theoretical principles in dealing with problems connected with the cross-magnetising flux were made by Messrs. D. Bruce Peebles and Co. in their early forms of dynamos and motors. Although these have now been generally superseded by the method of interpoles, they are still of such interest as to merit a brief reference as showing how theory can be, and has been, applied to practice.

In these machines the method used consisted in throttling the cross-magnetising flux by a central gap through the core of the field-magnetising

coil, and also in modifying it at the polar horns by specially shaping the pole tips. Fig. 107 gives the details of the field-magnet part of the magnet circuit at one pole of a four-pole machine which had an output of 66 kilowatts. There is a central slot in the pole core extending throughout the

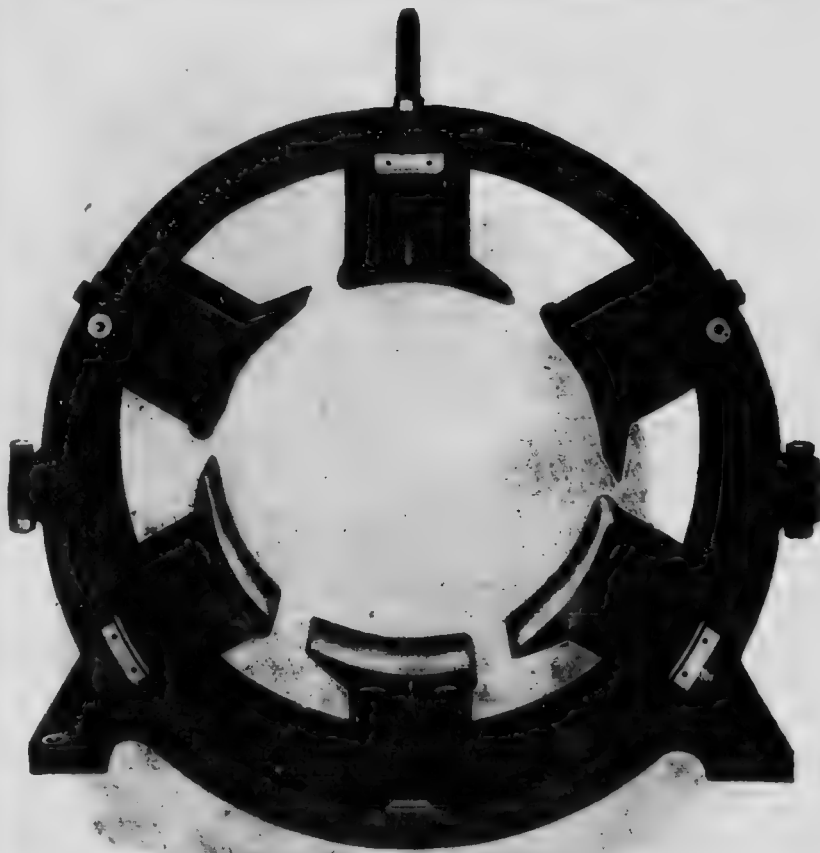


Fig. 106. — Field-Magnet Carcase of Johnson-Lundell Dynamo.

field casting from the yoke to the added pole face. The pole face, which is screwed on to the core by countersunk steel screws, has projections at the horns, and the proportions of these projections and the width of the air gap were finally determined by experiment so as to obtain the best effect for each standard machine. In large machines the leading and trailing horns were not symmetrical, the latter, for reasons set forth above,

projecting much more than the former. The 66-kilowatt pole piece of Fig. 107, however, has the leading and trailing horns exactly equal, allowing the machine to be run as a motor in either direction:

The method of applying the pole faces is worthy of notice: A cast-

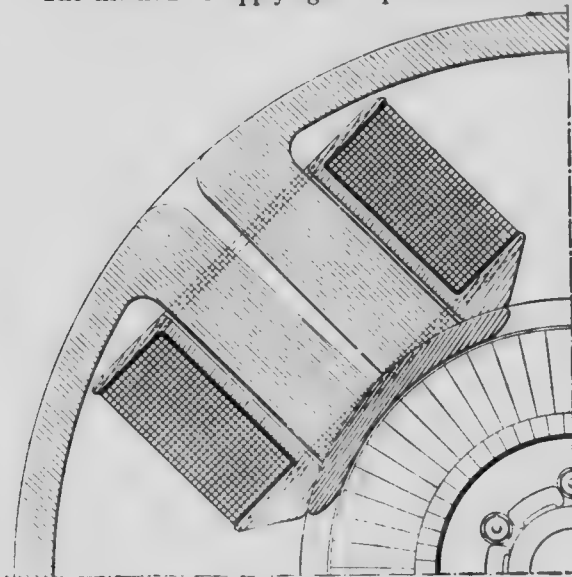


Fig. 107.—Pole Face and Slotted Core of a Bruce Peebles Field Magnet.

iron ring of the required diameter and width, and of a thickness determined originally by experiment, was cast in two halves to correspond to the steel case. This ring was carefully machined and accurately fitted to the bored polar ends of the cores: It was then cut through between the poles, connecting webs being left at the two edges as shown diagrammatically in Fig. 108, which represents the pole ring cut through and laid out flat. The pole

tips were given the correct shape, and the ring, when screwed on to the pole cores, held the magnetising coils in their places. The connecting webs gave stiffness to the whole, and their magnetic short-circuiting was slight. The pole ring as placed in position in a six-pole dynamo can

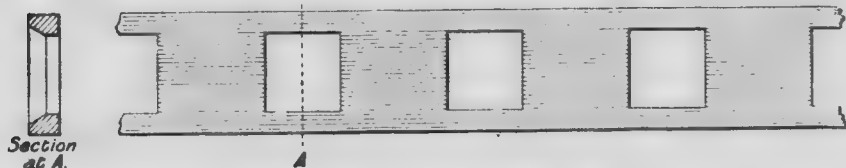


Fig. 108.—Pole Ring in Bruce Peebles Dynamo.

be clearly seen in Fig. 109, in which the shaping of the pole tips can also be made out.

In the larger machines the bobbins on which the magnetising coils were wound were made of cast iron, thus adding to the magnetic circuit additional magnetic material of low permeability, usually referred to as an *auxiliary magnetic circuit*. These bobbins with their heavy flanges materi-

ally affected the flux, they became saturated at low densities and promoted the sparkless running of the machine.

As a contrast to these now historical methods, Figs. 110 and 111 give



Fig. 109.—Field Magnet showing Pole Ring in Position.

details of corresponding parts to Figs. 107 and 108, as used in the machines which have succeeded them. In these figures we have sections of the magnet core and pole tips of a motor built by Messrs. Bruce Peebles

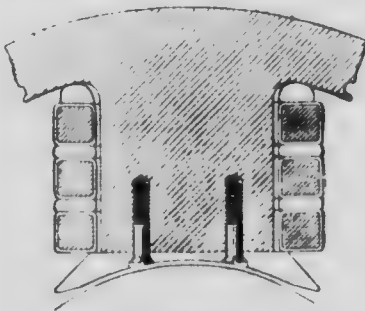


Fig. 110.—Section Perpendicular to Shaft.

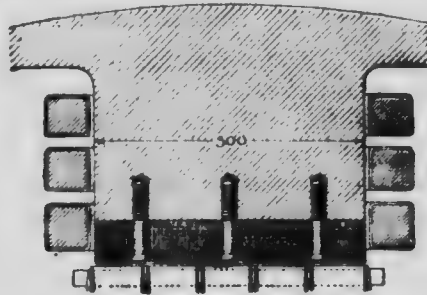


Fig. 111.—Longitudinal Section.

Pole Face and Core of Bruce Peebles and Co.'s more recent field Magnet.

and Co., which is to give 60 H. P. at 400 to 800 R.P.M. The core is solid, but the polar face is laminated, and the pole tips are carefully chamfered off to give a widening gap at the leading and trailing horns. In Fig. 112 a whole magnet ring is shown, including the series-wound interpoles, which have rendered the devices previously described unnecessary. This ring, however, is for a large machine having an output of 500 kilowatts: The use and theory of these interpoles is elsewhere described (*see* pages 107 to 111).

Another good example of devices used before interpoles became fashion-

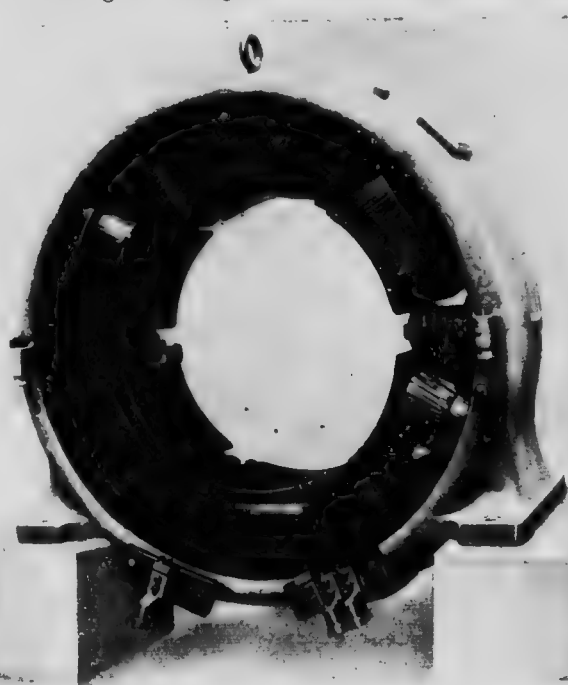


Fig. 112.—Field Magnet, with Interpoles, of Bruce Peebles Continuous Current Generator.

able is illustrated in Figs. 113 and 114, which represent diagrammatically a form of pole face used by the International Electrical Engineering Company. Here a special laminated pole face was screwed on to a solid circular core, on which the magnetising coils were placed. The laminations of this pole face were alternately long and short, and shaped as shown at *a b* and *c d* respectively. They were assembled to the required number,

and firmly bolted together between the short thick end plates *A A*. The effect of the construction was that the longer polar tips had only half the permeance of the pole face farther back, even if the permeability were the same; but as the flux density would be higher the permeability would also be less, and therefore the permeance would be still further reduced. Moreover, the face of the tips of the long plates was not concentric with the armature, but was raked back, thus diminishing the permeance of the air gap: The whole effect, therefore, was that the flux was choked back from the extreme pole tips, so that the excessive crowding of the lines shown in Figs. 479 and 480, Vol. I., could not

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occur at the trailing polar horn, whilst a well-distributed fringe for a reversing field was formed at the leading horn:

(c) *Commutating Armature Coils.*—Taking up now the third method specified on page 105, namely, the production of a reversing E. M. F. in the circuits of the sections short-circuited by the brushes, Sayers, with this object, introduced coils into the connectors between the main coils and the brushes. In an ordinary closed-coil winding, whether of the ring or the drum type, connections to the sections of the commutator are usually made by conductors which should be quite outside the working field of the dynamo, and

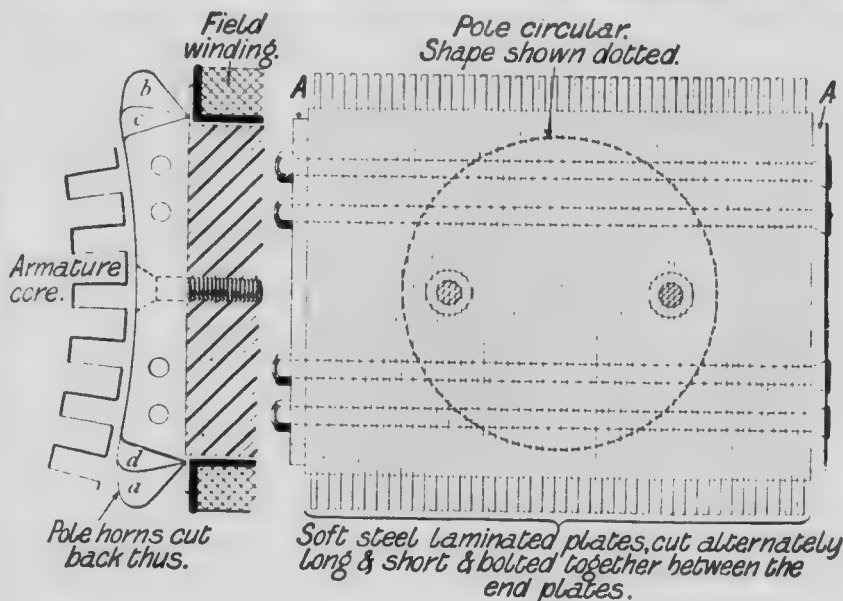


Fig. 113.—Section.

Fig. 114.—Polar Face.

The International Electrical Engineering Company's Laminated Pole Face or Shoe.

in which, therefore, no E. M. F.'s are induced in any position. If, instead of these simple connections, the paths to the commutator bars from the closed-coil winding are through additional windings placed close to the active windings of the armature, these additional windings will have E. M. F.'s induced in them of a magnitude depending on their positions with respect to the field flux. Such E. M. F.'s, however, during the greater part of the period of revolution, are not in any closed circuit, and it is only when a brush rests upon the commutator bar to which one end of the additional winding is attached that the circuit of that winding is closed.

One of the possible arrangements is represented diagrammatically in Fig. 115, which shows a lap winding of several coils connected to six com-

mutator bars by six special connectors. The poles are indicated by the black rectangles, being represented with the windings as laid out flat, and the conductors are supposed to be moving from left to right. At the

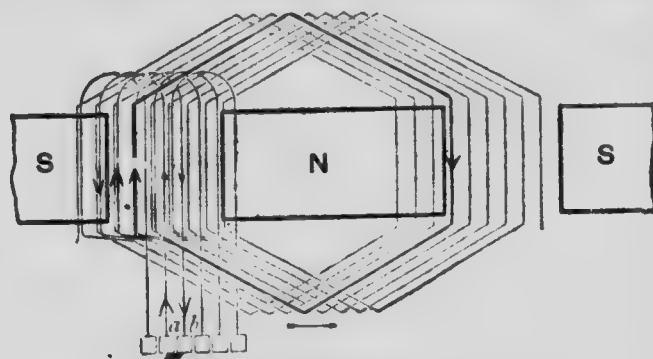


Fig. 115.—Sayers Commutating Connectors on Armature.

moment selected the brush B is short-circuiting the section shown by the thick line, and which is joined to the commutator by the connectors *a* and *b*. The direction, in the section, of the current which

has to be reversed, and the consequent direction of the current in *a* and *b* at the beginning of the commutation, are shown by barbs on the respective lines. The connector *a*, where it passes under the *s* pole on the left, has

a back E. M. F. in it which exceeds the forward E. M. F. in the same part of the connector *b*, and thus the effect on balance is to assist reversal. If in addition the *s* pole be extended by a reversing lug *P*, as shown in Fig. 116, it will be seen that by placing the right-hand winding of *b* in

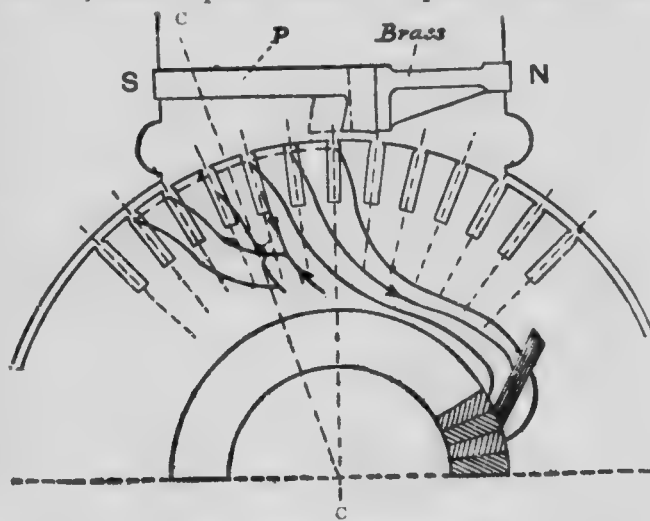


Fig. 116.—Sayers Commutating Coils.

a stronger *s* field than the corresponding part of *a* an additional reversing E. M. F. is, on balance, introduced into the short-circuited system.

Sayers calls the connectors "commutating coils." They need not be, and are not (in Figs. 115 and 116), on the same part of the field as the

armature section dealt with, and by properly choosing their position relatively to the armature section it is obvious that they may be so placed, as in the example just given, that the E. M. F. in them may be a reversing E. M. F. of the requisite magnitude to secure sparkless commutation. The value of the E. M. F. required should be determined by the principles already discussed (see page 105). So completely is the reversal of the current in the section under commutation brought under control by this method, that Sayers was able to run his dynamos with the brushes lagging instead of leading, as shown by the line c c, which denotes the angular position of the coil under commutation. In consequence the demagnetising effect of the armature current was eliminated, and no allowance was required to be made for it in compounding the machine—in fact, with a sufficiently large field the armature produces a magnetising effect which may be made to do the work, or part of the work, of the series coils in the compound winding. The form of slot used by Sayers is shown in Fig. 27, c; the commutating coils are wound in the upper part of the slot, and the working coils in the narrower and longer slot below.

Reactance Voltage.—In the process of commutation, as already remarked, the condition to be fulfilled for a perfect result (see page 105) is that the coil or section which is short-circuited whilst carrying a current in one direction should, just at the instant that the short circuit is about to be removed, be carrying in the opposite direction an equal current generated by magneto-electric induction during the period of the short circuit.

Now, in dealing with alternate currents, we have found that whenever a current changes from one value to another there is an induced E. M. F. in the circuit depending upon the rapidity and magnitude of the change and upon the inductance (L) of the circuit. The usual custom is to refer to this induced E. M. F. as a *reactance voltage*, which is quite correct, and to calculate its value on the assumption that the changes of current follow a *sine law*, an assumption for which no good theoretical reason can be given. On the contrary, the mathematical solution of the fundamental equation (see page 538, Vol. I.) of an inductive circuit,

$$RC + L \frac{dC}{dt} = E,$$

when E is either zero or practically constant, leads to a logarithmic equation for the current, as already mentioned on page 104. It follows that the constant factor is the *time constant* $\frac{L}{R}$ of the short-circuited coil, and not the so-called reactance voltage which is assumed to have the value pLC , where C is the current to be reversed, L is the inductance of the short-circuited coil, and $p = \frac{2\pi}{T}$, the symbol T denoting the time of one complete sine-wave period, usually assumed to be the time of short circuit. From the

point of view of this theory it is asserted that low-reactance voltage is more important than great field-magnet strength, and that in no case should the reactance voltage exceed three volts. Both ways of viewing the facts require that the value of L should be low, but the defect of the reactance-voltage theory is that it takes no account of the resistance of the short-circuited coil which all experience shows has a very material influence on sparkless commutation.

As regards L , it is worth noting that for slotted and tunnelled drum armatures the value of L is greater than for smooth-core armatures, because the

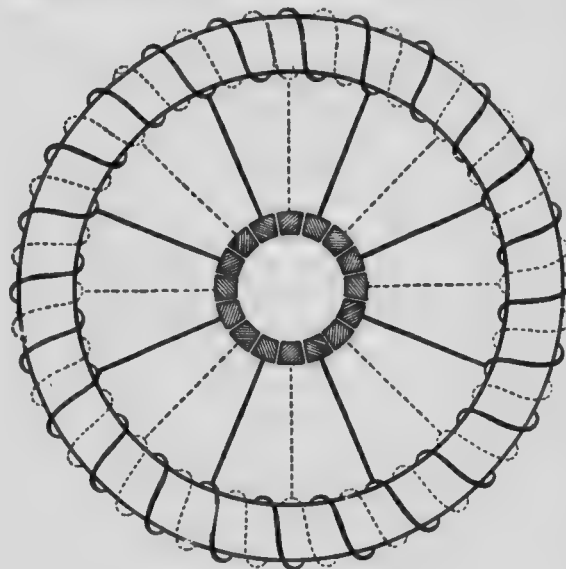


Fig. 117.—Diagram of Multiplex Windings.

section under commutation is more or less completely imbedded in iron; hence, other things being equal, the difficulties of good commutation are greater. It is, however, somewhat surprising to find how much of L in practice is due to the end connections, even in slotted armatures. Mr. Hobart has shown that as much as 25 to 40 per cent. of the total inductance may be due to this cause. In ring armatures, since the wire of each section encloses the whole cross section

of the armature iron, the value of L is relatively high. In all cases it depends on the square of the number of turns per section under commutation, and the necessity for keeping it low is therefore an argument in favour of commutators with numerous segments.

Multiplex Windings.—Where heavy currents have to be dealt with the inductance of each commutating section can be reduced by winding the armature with two or more distinct re-entrant circuits, the turns of each circuit following one another in a regular sequence on the surface of the armature, and the commutator bars of the different circuits being interleaved on the commutator.

The method as applied to a ring-wound armature is shown in Fig. 117, in which it will be found that the full line and the dotted line windings form two entirely distinct circuits insulated from one another. Each

circuit is represented as consisting of 24 turns, and has eight bars on the commutator. The brushes must obviously be sufficiently thick to span across the intervening segment of the commutator so as to short-circuit each section properly in turn, and to keep it short-circuited sufficiently long to allow of sparkless reversal. The result will be that the total current will be divided between the two circuits of the *duplex winding*, as it is called, and that in each section only one-half the current has to be reversed which would have to be reversed if the winding were the ordinary or *simplex winding*. The extension of the principle to *triplex winding*, in which the current per section for reversal is reduced to one-third, is obvious.

An incidental advantage of multiplex winding is the removal of the danger of the sections of the armature becoming short-circuited by the insulating strip being bridged by a particle of copper or other conducting material. The eddy current loss in the copper is also reduced by the conductors being cut up into bars of smaller cross-section.

Equalising Circuits.—A fruitful source of sparking at the brushes, especially in large multipolar machines, is due to the fixed pole faces and the face of the revolving armature not being exactly concentric. Even if the machine be at first mathematically perfect in this respect—a result difficult to obtain with large machines similar to that depicted in Fig. 12—uneven wear at the bearings may throw the revolving part out of truth. With the narrow air gaps used in modern dynamos, if we suppose the bearings to wear down $\frac{1}{16}$ inch, the gap at the top will be appreciably widened, whilst that at the bottom will be correspondingly reduced. Bearing in mind (see page 49) the very important part which the air gap plays in the total reluctance of the magnetic circuit, these small changes will evidently produce a very appreciable increase of reluctance and consequent diminution of flux at the upper poles, and a corresponding decrease of reluctance and increase of flux at the lower poles. The E. M. F.'s generated in the upper and lower parts of the armature will therefore no longer be equal to one another, and the potentials of the brushes placed in parallel on the collecting rings will differ. As these rings have a very low resistance, even a small difference of potential will lead to heavy equalising currents passing through them, with a consequent production of heat and loss of energy. But the mischief does not stop there, for these heavy extra currents must pass through the brushes and be commuted with the actual load currents. Such a great increase in the currents under commutation must inevitably lead to copious sparking, for the devices for sparkless commutation will be unable to deal with these abnormally large currents; in addition, much extra heat must be developed in the armature.

To meet the difficulty the General Electric Company of America and others use cross-connections inside the armature, a sufficient number of points in the winding, which theoretically should always be at the same

potential, being joined by heavy copper conductors. These conductors may be placed at the back end of the armature, as shown in Fig. 118, each one consists of an insulated bar of copper *c*, bent into the shape of a circular arc, and connected at selected points to the armature windings. Another position used for equalising connectors is the space between the core and the ordinary vertical connectors to the commutator bars. In Fig. 31 the equalising connectors can be seen lying on this space



Fig. 118.—Equalising Connections in a Multipolar Armature.

on a large unwound Dick, Kerr armature. All the selected points for any one connector are normally at the same potential, and in that case no currents flow in the connector. If, however, owing to the decentering of the armature or any other cause, the fluxes through the different poles become unequal, these points are no longer at the same potential, and more or less heavy currents will flow in the connecting bar. The currents produced in the bar will be *alternate currents*, for it is obvious that the P. D. between any two points will reverse

as the armature revolves. According to Lenz's law, these alternate currents will tend to remove the causes of their production—namely, the differences of pole flux; being in inductive circuits they will be out of step with the P. D.'s producing them, but this will tend to increase their compensating effect. Incidentally this compensating effect has another virtue. Any difference of magnetic flux in different parts of the polar ring gives rise to differences in the magnetic pulls, which therefore get out of balance (see also page 28). In extreme cases the differences may amount to forces of thousands of pounds' weight. The equalising rings, therefore, not only lead away the heavy equalising currents from the brushes and diminish

the sparking, but the resistance of the equalising circuits being smaller, the compensating effect of the currents in them on the differences of polar flux, and consequently on unbalanced magnetic pulls, is more efficacious.

VII.—MECHANICAL DETAILS

Dynamos and electric motors being machines in which, especially in the larger types, great mechanical forces may be developed, and whose moving parts in many instances spin, as a whole, at high velocities, have to be designed very carefully to resist these mechanical forces and to ensure that the rotors shall run smoothly at, and over, their normal speeds. The mechanical problems are complicated by the necessity for securing the adequate insulation of the electric circuits from one another and from the other conducting material of the machine. The two sets of problems interact and are further complicated by the mechanical weakness of some of the materials available for insulation. It is proposed, therefore, to devote a fair amount of space to the consideration of the more important problems in detail, and to illustrate the principles involved by examples of successful solutions drawn from various sources.

Driving the Core Discs.—The necessity for a good mechanical connection between the core discs and the shaft has already (page 596, Vol. I.) been referred to in the case of electric motors, and similar reasons apply in the case of dynamos, for the power of the engine has to be transmitted from the engine shaft to the core and the copper windings upon it, as it is in these windings that the transformation from mechanical to electric energy takes place:

In two-pole machines one method is to key the core discs directly on to the shaft, securing them by suitable end-plates held in their places by nuts and lock nuts on the shaft. This method is illustrated in the core disc stampings already shown in Fig. 28, in each of which will be noticed a notch for the keyway which is to secure the completed core to the shaft. It cannot be used with ring-wound armatures, and has the disadvantage of bringing the core iron down close to the shaft, increasing the difficulty of efficient ventilation and also the losses by hysteresis. To obtain better ventilation the necessary mechanical drive is often given to the core discs either by the latter keying on the arms of spiders which are fixed to the shaft or by clamping plates at each end, these plates carrying bolts which pass straight through the layers of discs; the clamping plates in their turn are often carried by spiders fixed firmly to the shaft:

A core disc, the core built up from which is to be keyed on to the arms of a three-armed spider, is shown at B, Fig. 119; the notches *a*, *b* and *c* are for the keyways. On the other hand the stampings shown at A and C are intended to be made secure by bolts. At A the stamping shows lugs *a* *b*

and *c* on its inner periphery through which the bolts pass, while at the bolt holes pass through the middle of the iron ring.

In some of the direct-coupled machines built by Messrs. Brown, Colverson and Co. the armature

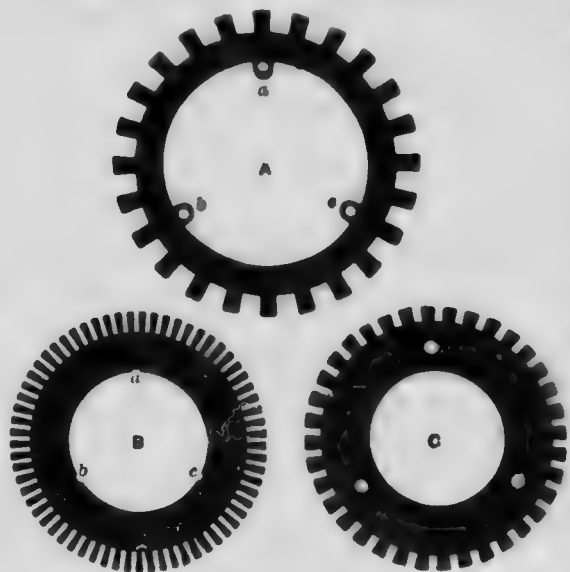


Fig. 119.—Core-Disc Stampings, Showing Methods of Driving.

has three large ventilating holes stamped out of it as shown. In addition they are held firmly in place by end clamps, and extra ventilation is provided by no fewer than three wide radial interspaces in a total axial length of only 190 mm. (7.5 inches).

The method of driving the core discs in large multipolar machines has to be carefully designed. A very general plan is to key the discs on to a substantial spider, which in

and Co. the armature spider, Fig. 120, is extended beyond the limit of the armature to the coupling which connects the dynamo to the engine, thus giving additional stiffness to the spider and more direct transmission of the power. This method is also shown in Fig. 60.

In the four-pole machine by the same firm, all particulars of which are given in Plate I., the core plates, being only 330 mm. (13 inches) in diameter, are keyed directly on to the shaft, and each plate

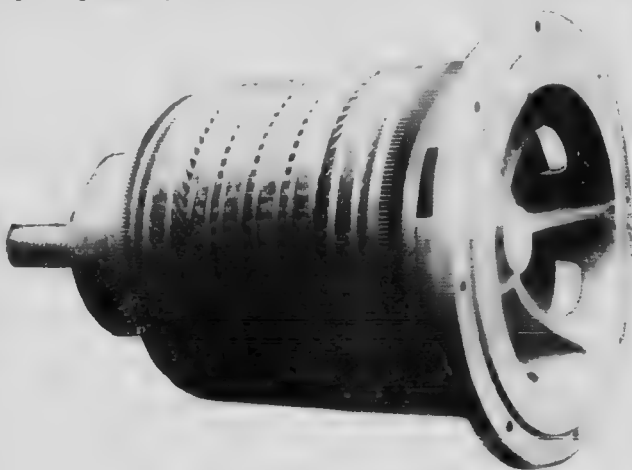


Fig. 120.—Armature Spider extended to Engine Coupling

turn is keyed on to the shaft. It will be remembered that in the machines the discs do not form complete circles, but are built up of segments of circles (see pages 33 and 35), a fact which adds to the difficulty of obtaining a satisfactory drive. One of the earliest designs made some years ago by the English Electric & Dynamo Co. (now Messrs. Dick, Kerr and Co., Ltd.), at London, was constructed of strong and tough cast iron, and was of the

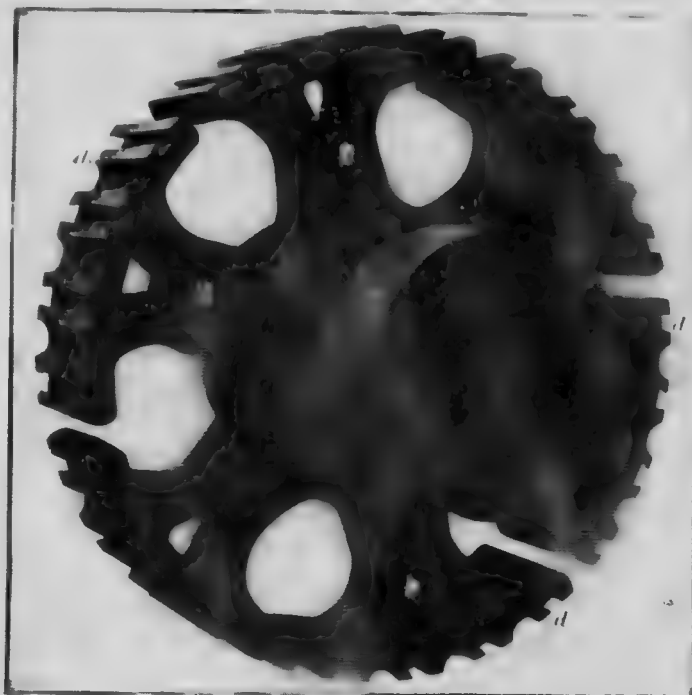


Fig. 122. Dick, Kerr Multipolar Dynamo.

as the casting of the segments was not continuous at the circumference, the segments were divided into more than six sections in the example given. The segments are more numerous. The segmental pieces are stamped, after being stamped, to reduce the weight to a minimum, and japped on one side to prevent the flow of currents. They are then placed in position in the manner shown in Fig. 122. The spider is supported vertically, and, proper supports being arranged, the segments are put up. The inner edges of the segments are stamped with dovetail slots, which accurately fit the undercut dovetailed slots in the rim of the spider. The slots of the external teeth

of the core are kept in alignment by the little upright strips placed at intervals round the rim as the discs are being put in position. When a sufficient number of discs has been threaded on they are firmly clamped in their places by cast-iron flanges at each end bolted together through the bolt holes *b b* of the spider. The discs and spider then form a very compact whole from a mechanical point of view, the dovetailed connection between the two giving an excellent drive when power has to be transmitted from one to the other. The spider itself is very firmly connected



Fig. 208.—Building up a Multipolar Armature Core.

to the driving shaft. The central boss is bored out accurately to a slightly smaller diameter than the shaft, and is then pressed on with a force of about 100 tons; it is afterwards secured from slipping round with two keys.

The Commutator.—The commutator is undoubtedly the weakest part of a continuous current dynamo, and, therefore, the part to which special attention should be given in the design. It is the only electrical part subjected to continuous frictional wear, and its renewal when worn out is a costly operation. Every precaution which will tend to diminish the rate of wear should therefore be adopted, and more especially does this apply to the care with which the commutator should be looked after when the machine is in use.

Electrically, the commutator bars must be well insulated from one

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another and from the shaft of the dynamo. For the former object, after experience with many materials, thin sheets of mica are now practically the only insulators employed. These sheets can be obtained of any required thickness to within a thousandth of an inch and cut to any template. For insulation from the shaft, sleeves and rings of ebonite, micanite or other good insulating material of sufficient mechanical strength, are employed. The cross-section of these depends on the design of the copper bars. The latter are now always made of hard-drawn or drop-forged high conductivity copper, and some makers compress them further hydraulically when building up the commutator. Bars of good firm copper, properly attended to when the machine is first run, rapidly acquire on the rubbed surface a polished skin, which reduces the wear to a minimum. As there is sometimes considerable friction at the surface of the commutator, it must be so designed that it is rigidly connected to the driving shaft. The various bars must also be very firmly bound together, so that on the one hand the possibility of a bar "dropping" slightly, so that its outer edge is a little below the general cylindric surface, is reduced to a minimum, and on the other hand the tendency of the wedge-shaped bars to fly outwards by centrifugal action is restrained. The latter tendency becomes abnormally great in high-speed turbo-dynamos, necessitating special clamping rings to counteract it; examples of these will be given later. Lastly, in drafting the original design, the fact that the different parts of the commutator have to be assembled and built up together must not be overlooked, for it is quite easy to put a design on paper which if completed would be mechanically and electrically perfect, but which it would be very difficult or even impossible to build.

With the foregoing requirements borne in mind, we shall now examine some drawings of actual commutators. In small bipolar machines the commutator is usually built directly on the shaft, and we show in Fig. 123 the details of the commutator of the Johnson and Phillips overtype machine, illustrated in Fig. 608, Vol. I. In this case a specially-shaped gun-metal sleeve *r r* is keyed on to the shaft, its position with respect to the armature being fixed by an enlargement of the shaft from 2.5 to 2.75 inches diameter. The end of the sleeve

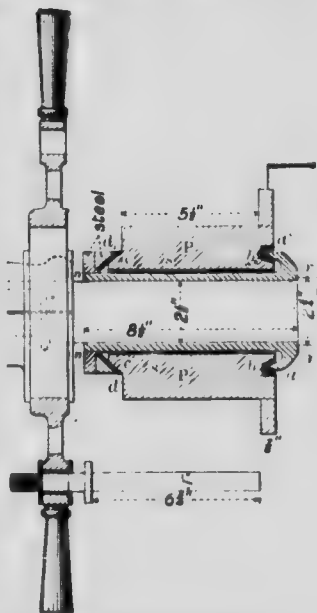


FIG. 123.—Commutator of Johnson and Phillips' Bipolar Machine.

is splayed out and forms a hollow annular space bounded by a projecting rim *aa*. This rim is covered with a suitably shaped ring *bb* of ebonite, which fits over it, and a long sleeve *ss* of ebonite is slipped over the greater length of the gun-metal sleeve. If the shaft be now placed in an upright position, the copper plates *pp* interleaved with mica, both of the shape shown, can be assembled in place, resting on the gun-metal sleeve during the process. The whole having been brought

together and tightly clamped up, a conical ebonite ring *cc* is placed over the projecting lugs at the left-hand side, and is held in place by a coned steel ring *dd*, the whole being clamped up tightly by a nut *nn* which is screwed on to the end of the gun-metal sleeve. The ebonite rings and sleeve serve to insulate the copper from the metal supports, and the mica insulates the copper plates from one another.

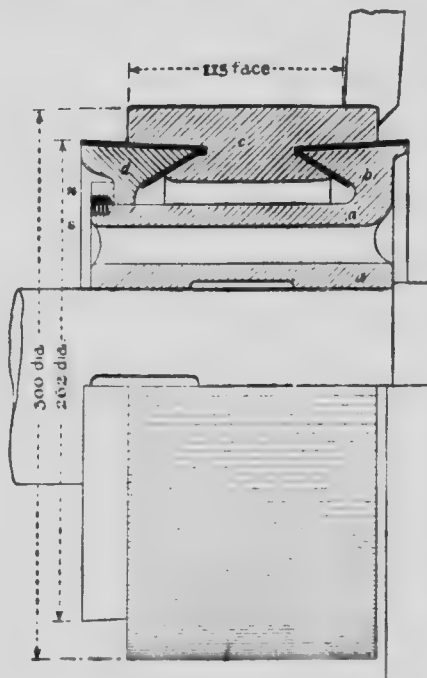


Fig. 124.—Commutator of a Four-Pole 60-H.P. Motor.

Multipolar Commutators. — In many multipolar machines the diameter of the commutator is so large that it cannot be built up directly on the shaft, but has to be supported by a spider keyed or otherwise rigidly attached to the shaft. The Bruce Peebles, Crocker-Wheeler and some other machines have the commutator supported by a direct extension from the spider, which supports and drives the core discs of the armature.

An example of a spider-carried commutator for a machine not much larger than that dealt with in Fig. 123 is shown in Fig. 124. This is taken from a 60-H. P. four-pole motor built by Messrs. Bruce Peebles and Co., designed to run at 400 to 800 R. P. M. when supplied with current at 440 volts. The spider *aa*, securely keyed to the shaft, carries a conical annular ring *b*, which is in one piece with the rest of the spider. This conical ring, having been covered with micanite insulation, as shown by the thick black lines, is stood on end, and the copper and mica commutator segments *c*, with corresponding notches, are assembled round it. The further micanite insulation, shown on the left, and the clamping ring *d*, having the cross-section as shown, are then driven home, and held in place by the annular nut *n*, which

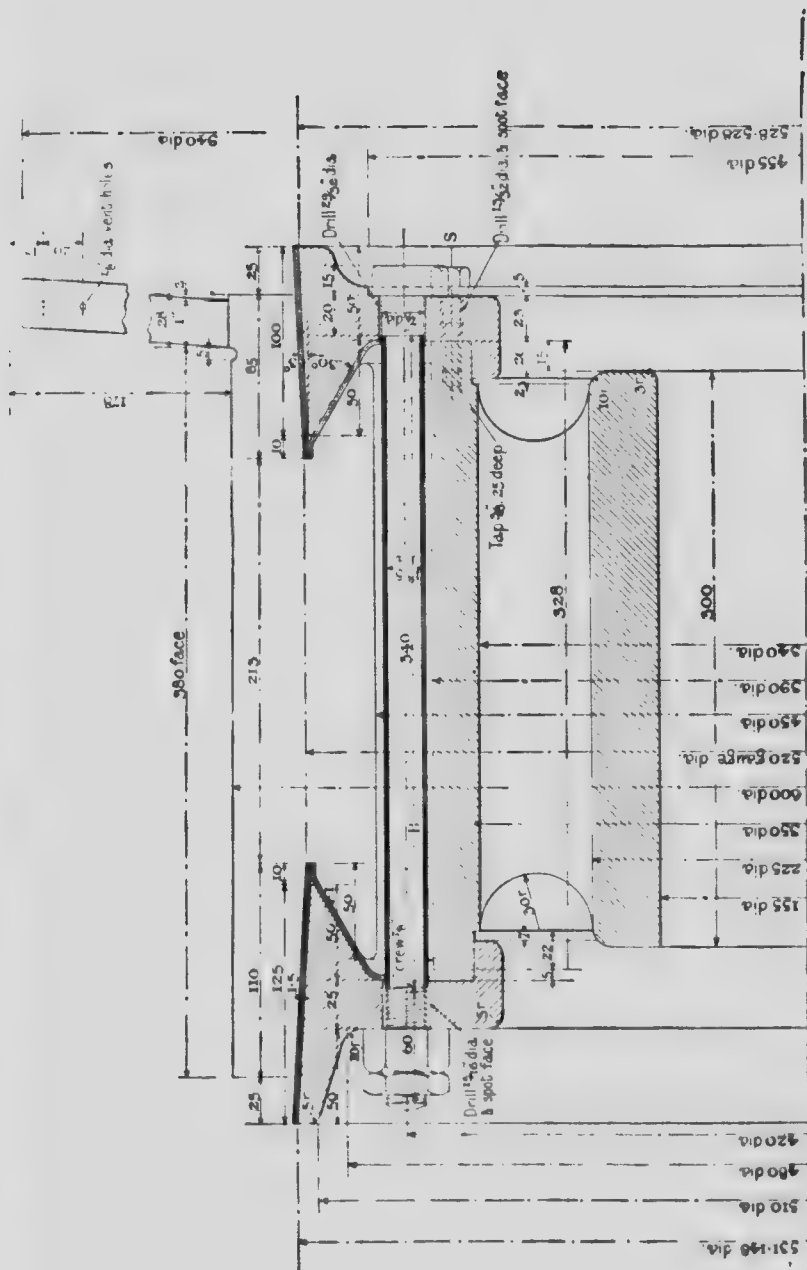


Fig. 125. — Bruce Peebles Commutator constructed for a 1,000-Ampere Dynamo.

in its turn is secured by screws *s*. The dimensions on the figure are in millimetres. The lower half of the drawing shows the completed commutator.

Very full particulars of a modern commutator for a much larger machine are given in Fig. 125, which is reproduced from a working drawing kindly supplied by Messrs. Bruce Peebles and Co. The dimensions given are in millimetres, and the scale is very nearly, but not quite, one-quarter of full

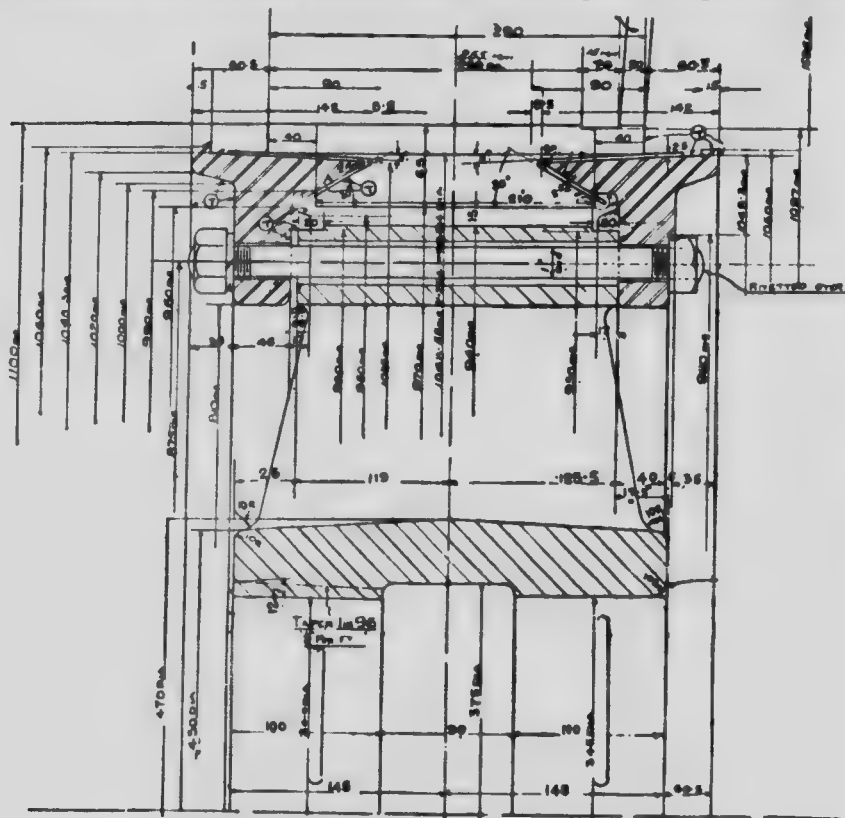


Fig. 126.—Modern Multipolar Commutator of Messrs. Mather and Platt.

size. The drawing is of a commutator for a six-pole machine, with an output of 1,000 amperes or 333 amperes on each set of brushes, which is very nearly one ampere for each millimetre length of the working surface of the commutator. The general plan is similar to that of Fig. 124, but there are some important differences. The conical ring *b*, of Fig. 124 is in the larger machine separate from the spider to which it is firmly attached by the bolts *B*, of which there are twelve, and which also hold in place the clamping ring *d* (Fig. 125). Both rings have good bearing surfaces

fitting the inner side of the spider cylinder, and the nuts which tighten up the bolts are provided with locknuts to prevent them working loose. As an additional precaution, the ring on the right-hand side is further held in place by six screws *s* equally spaced between the bolts. Other interesting details can be readily made out by inspection.

In Fig. 126 dimensioned details are given of one of their standard type of commutators designed by Messrs. Mather and Platt for their large dynamos, fully described elsewhere. The dimensions given are in millimetres. The commutator is carried on a spider 940 mms. (39'4 inches)

in diameter, and 144'5 mms. (5'7 inches) wide at the end of the supporting arms. To these are bolted the steel rings which carry the insulating rings and the copper bars and mica sheets of the commutator itself. The shape of the latter and the method of assembling can be inferred from the drawing. The extreme dimensions of the copper bars are 65 mms. (2'5 inches) deep, and 290 mms. (nearly 11'5 inches) long, and of this length about 9 inches is available for brushes. The external diameter of the copper surface of the commutator, when finished, is

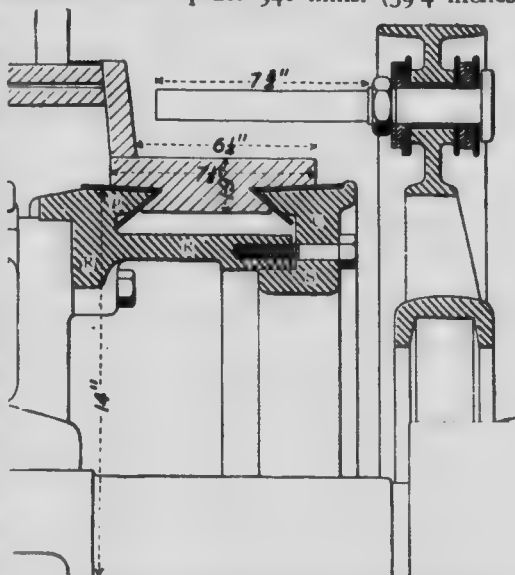


Fig. 127.—Multipolar Commutator of the International Electrical Engineering Company.

1100 mms. or 43 inches, above which the lugs for connecting to the armature windings project 247'5 mms. or about 9'8 inches. Other interesting details can be made out from the drawing, which will repay careful study.

The International Electrical Company attach the ring *RR* (Fig. 127), which supports the commutator, directly by bolts to the arms of the armature spider. The cross-section of this ring has a projection *p* sharply bevelled below and slightly bevelled on top, over which is slipped the V-shaped insulating ring, which carries the parts of the commutator. The clamping ring *c* has a large bearing surface at *s* underneath *RR*, and engages in the other V notch in the commutator bars. When bolted up into its place the bevels on both sides are such that the commutator parts are very firmly drawn into and held in position.

Commutators for Turbo-Dynamos.—It has already been pointed out

more than once that in turbo-dynamos the design of the commutator has to be modified to meet the special conditions. At the high speeds at which these machines run, the number of pairs for a given voltage and output is necessarily less than in slower-speed machines, and therefore the amount of current to be collected by each line of brushes is correspondingly greater. If, further, the conditions, as is usually the case, allow only a single commutator, this commutator, if of the ordinary type, will have to be abnormally long and also of a small diameter relative to the amperes to be handled. Sufficiently long copper segments could, of course, be mounted in some of the ways already described, but it is found that, however well clamped at the ends, such segments have a dangerous tendency to fly outwards at other points when run at the high speeds of the turbines, this tendency being still further assisted by

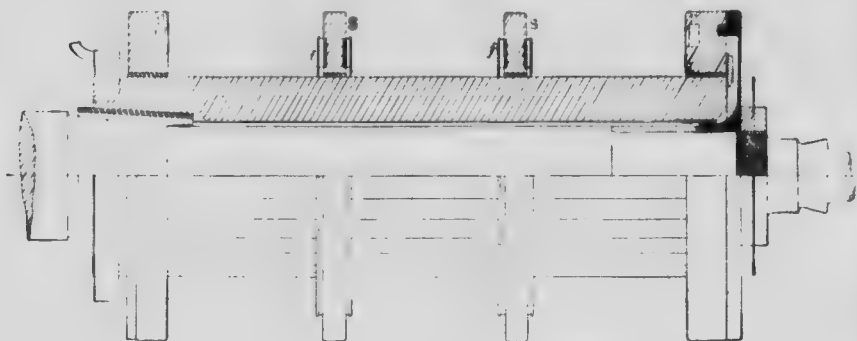


Fig. 128.—Commutator for Parsons Turbo-Dynamos.

the greater slope of the wedge-shape bar, due to it being part of a commutator of smaller diameter.

In most of the machines, therefore, it is found necessary to introduce auxiliary clamping rings at intermediate positions along the face of the commutator, as there is no other method nearly so effective for counteracting the large centrifugal forces developed at high speeds. The number of rings necessary depends on the length of the commutator, its diameter and speed.

This principle was adopted as far back as 1890 by the Hon. C. A. Parsons in the early days of steam turbines and turbo-dynamos, and long before the latter had come into general use. Its application is well shown in Fig. 128, which depicts, partly in section, one of Messrs. Parsons and Co.'s standard types of commutators. Instead of the surface of the commutator being quite clear between its end supports the figure shows two steel rings *s s* shrunk on to the bars at intermediate positions, but of course insulated from the bars, the insulation being clearly shown in the sectioned half of the drawing. The method of shrinking on is

described later (see page 145). The rings also carry shrouded centrifugal fans *f f*, which ensure a circulation of cooling air round the commutator.

The commutator is supported at the end nearest the armature by a brass cone from which the bars are insulated, as shown. The method of support at the other end, with the necessary insulating rings and discs, can be made out. The special feature is a steel diaphragm plate, which is shaded black in the figure. This plate, which is held in place by a nut and locknut screwed on to the shaft, is so adjusted as to exert a steady pressure on the commutator bars in the direction of the armature. When the commutator gets heated the expansion of the long copper bar is greater than that of the steel shaft, not only because the coefficient of expansion of copper is much greater than that of steel, but also because the copper bars are raised to a higher temperature. By the use of

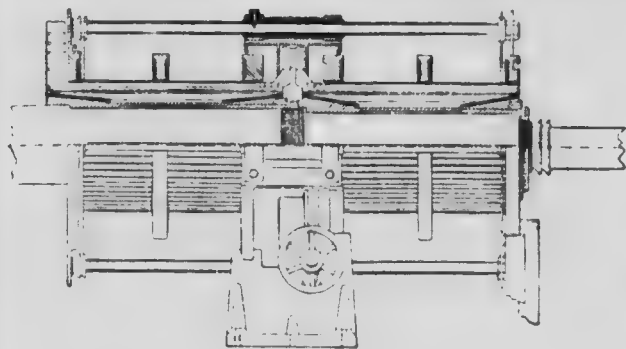


Fig. 129.



Fig. 130.

Sections of Siemens Ventilating Commutator for Turbo-Dynamos.

the diaphragm at one end and the brass cone at the other, the differential longitudinal expansion of the copper bars is allowed for without over-stressing the material. Actual sliding is assumed not to take place, for experience tends to show that if reliance be placed upon this the sliding surfaces sooner or later develop a tendency to stick.

In view of the high velocity and the friction consequent thereon, an important point to keep in view in designing the commutator is to make, as far as possible, provision for keeping the rubbing surfaces cool. In the Parsons' commutator just described fans are attached to the clamping rings. In the Siemens' commutator the copper bars used are hollow, and air is driven through this hollow space, thus removing the heat close to the points at which it is generated, and tending to keep the whole commutator cool. An early form of this commutator, partly in section, is shown in Figs. 129 and 130, whilst a picture of a completed commutator of the most recent pattern is given in Fig. 131. The commutator is made in two parts connected together by broad lugs, which act as fans when the

commutator is rotating, and drive a plentiful supply of air through the hollow bars. The ends of the hollow spaces can be clearly seen both in Figs. 130 and 131: By the splitting of the commutator into two parts the difficulties caused by the expansion of the long copper bars used in other patterns are partly overcome, and it is claimed that the commutator therefore



Fig. 131.—Siemens Ventilated Commutator.

keeps more accurately in balance: The effective cooling also makes it possible to use carbon brushes, with the consequential advantages alluded to elsewhere; and as the machines are also provided with commutating interpoles, very efficient and sparkless commutation is attained: The commutator depicted in Fig. 131 is the actual commutator used on the machine

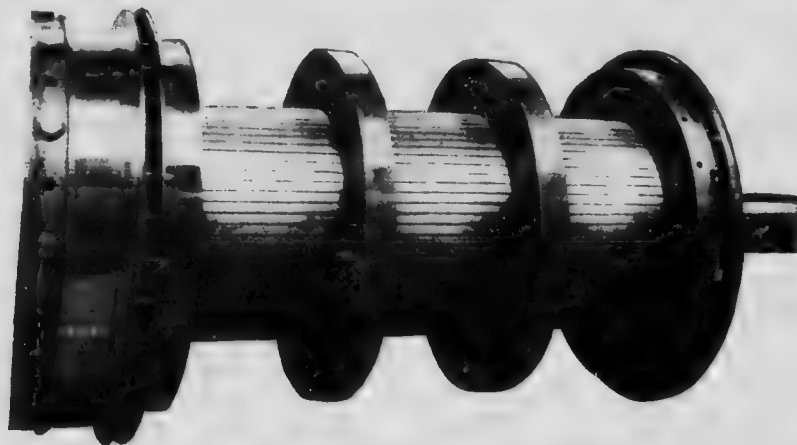


Fig. 132.—Brown, Boveri and Co.'s Commutator for Turbo-Dynamos.

illustrated in Fig. 9, page 15, and handles an output of 2,400 amperes at 500 volts when running at 1,250 R. P. M.

In Fig. 132 is shown the latest type of ventilated turbo-commutator as built by Messrs. Brown, Boveri and Co: The dimensions of a commutator of this type, as used on a 500-kilowatt machine to collect a current of 2,000

amperes at 250 volts, will be found in Plate IV., where it will be seen that the total length of the commutator bars is 1,190 mms. (47 inches), of which 800 mms. are exposed for the contact of the brushes. The external diameter of the commutator proper is 380 mms. whilst the steel rings, which are shrunk on, have an external diameter of 550 mms., an axial thickness of 65 mms. (2.6 inches), and a radial depth of about 80 mms. (3.15 inches).

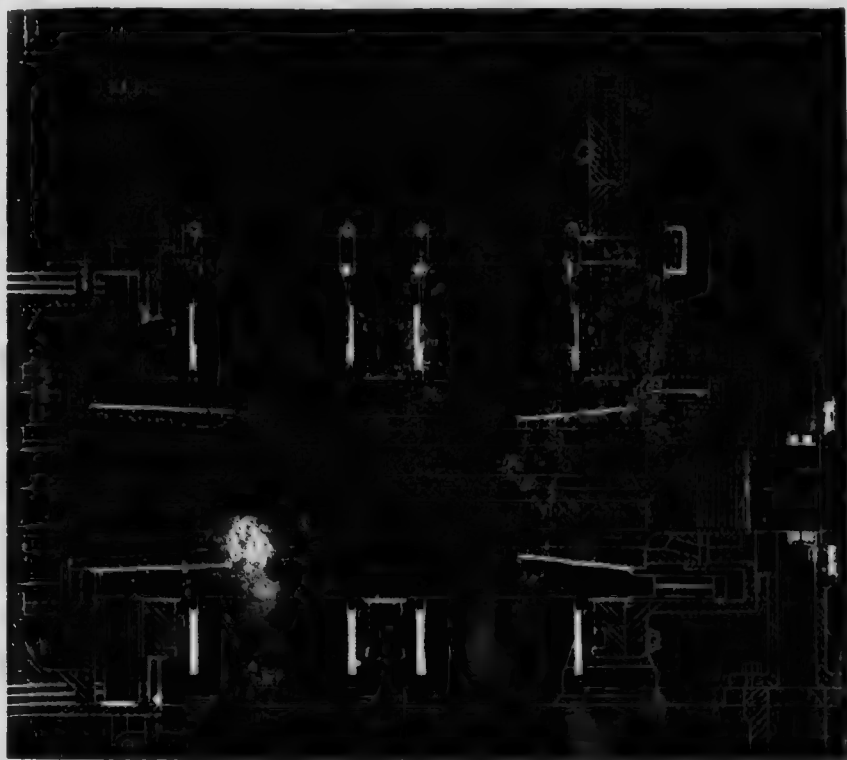


Fig. 133.—Section of Commutator for Brush Turbo-Dynamo.

These rings are shrunk on over solid mica insulating rings; a commutator in course of construction is shown on page 145 (Fig. 139).

As a still further example Fig. 133 gives a section of the commutator of the Brush turbo-dynamo already partly illustrated in Fig. 7. This commutator is required to give an output of about 1,500 amperes at 500 volts, and as the machine is a four-pole machine, each brush spindle must collect about 750 amperes. Allowing 40 amperes per inch of axial length, this current would require about 19 inches of working commutator surface. In Fig. 133 there is one central clamping ring of steel about $1\frac{1}{4}$ inch thick,

shrunk on so as to sit firmly on a slight projection in the centre of the commutator bars. There is mica insulation between the steel ring and the copper segments. In addition the bars are heavily clamped at each end, and to allow for these clamps and the lugs for the connections to the armature the total length of copper in each bar is 29 inches, of which only 17 inches is exposed as a rubbing surface for the brushes, which are of carbon. The diameter of the cylindric copper surface is 11.5 inches, which at the normal angular velocity of 2,400 R. P. M. gives a peripheral speed of 7,200 feet, or nearly 1.4 miles per minute. The coned end sleeves are slipped directly on to the axle, which is expanded, and the armature end coned to receive them.

At the bearing end the sleeve is of gun-metal, and is held in position by a spring washer to allow of expansion due to the heating of the commutator. Other details can be made out from the drawing. In still larger

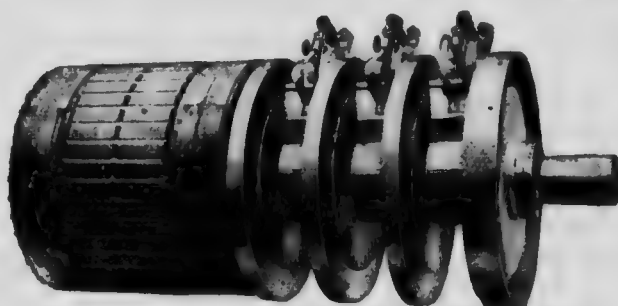


Fig. 134.—Armature and Radial Commutator of Westinghouse Exciter.

machines the commutator is mounted on a spider shaft, through which air is drawn to cool the inside of the commutator.

An important further modification is shown in Fig. 134, which illustrates the *radial* commutator

used by the British Westinghouse Electric and Manufacturing Company in one of the continuous current exciters of a turbo-alternator. The exciter is mounted on the alternator shaft, and the figure shows not only its commutator, but also its armature, which, as usual, is of much shorter axial length, notwithstanding the modification now being described. This modification consists in arranging the rubbed surfaces *radially*, that is in *vertical planes*. These radial surfaces can easily be made out in the figure, although each projecting set of bars is held clamped by the usual steel ring. The shape of the commutator bars is given in Fig. 135, in which can be seen the radial parts *aa* projecting from the usual long bars of copper. The horizontal parts of the copper not now being required as surfaces for the brushes, it is possible to place the clamping rings either on the top of the radial projections or at the bottom of the grooves formed by these projections. In Fig. 135, the insulating strips, but not the steel rings, are shown at *A* in the first position, whilst at *B* the rings and strips appear in the second position. A reference to Fig. 134 and other figures will show that the first position has been adopted in

actual practice. In Fig. 134 one set of brushes is shown projecting into the grooves between the different radial surfaces; the sides of the brushes rub against the surfaces, and the contact is not interfered with by the end play of the shaft, as this is slow in period and small enough in amplitude for the brush holders to adjust themselves to it. On the other hand, the rapid cross-axial movement of the shaft, which at high speeds is sometimes very pronounced and makes it difficult to keep the ordinary brushes in their place without excessive friction, has no effect on these radial brushes. Carbon brushes are used and their beneficial effect on the commutation is secured with an axial length of commutator not greater than would be required for copper brushes with their higher current density.

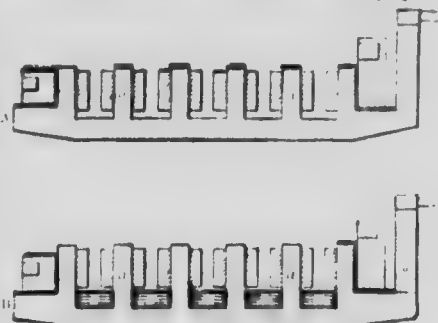


Fig. 135.—Commutator Bars for Radial Commutator

The radial commutator is, of course, applicable not only to the exciter of a turbo-alternator, but also to a large turbo-dynamo, and Fig. 136 shows the finished armature and the nearly finished commutator of a 250-kilowatt machine built by the Westinghouse Company to run at 3,000 R. P. M. The radial commutator segments are shown in this figure without the clamping rings which appear in Fig. 134, and which are required to hold the segments together against



Fig. 136.—Radial Commutator of a Westinghouse 250 Kilowatt, 3,000 R. P. M. Turbo-Dynamo.

the heavy centrifugal forces brought into play at the high speed of running, which it will be noted gives one revolution in one-fiftieth of a second; the omission of the rings exposes the ends of the commutator segments. Further reference will be made to these radial commutators in the section dealing with brush gear.

Building-up Commutators.—It will be readily understood that to bring the numerous parts of a large commutator into their relative places special devices have to be employed. An assembling ring as used by the General Electric Company, Ltd., for getting the copper and mica sheets into their

proper relative positions is shown in Fig. 137. Inside an outer ring *rrr* are a number of circular segments *ss* carried on pins projecting inward from *rrr*. The ring being on a horizontal table, the copper plates and insulating mica sheets can be put into position, and, when all assembled, can be tightened up by the bolts *BBBB* which press the circular segments *ss* inwards. When well tightened the whole can be slipped over the commutator spider or other support, and the processes of insulating and clamping completed.

Most firms have their special jigs and devices for the assembling of the commutator parts, the clamping of them tightly together, and their firm and secure attachment to the shaft or spider by which they are to be driven. Too much attention and care cannot be bestowed upon this important detail of dynamo construction. In many cases a hydraulic press by which a considerable pressure can be quietly applied is found to be very useful if not indispensable, so much so that special arrangements

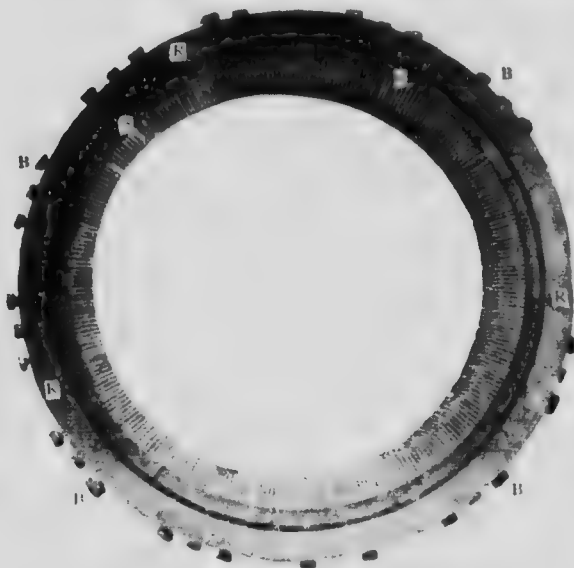


Fig. 137.—Assembling Ring for Large Commutators.

of hydraulic presses have been devised for this work. One such arrangement, made by the West Hydraulic Engineering Company, of Bradford, is shown in Fig. 138. The copper and mica commutator parts are assembled in an eight-part loose clamping ring as shown, the various sections being held together by the tightening bolts with which a fair initial pressure can be developed. The commutator so clamped is placed on a small table in the centre of the heavy yoke ring (Fig. 138), which carries eight hydraulic rams projecting inwards, the centres of the sections of the clamping ring being placed so as to face the inner ends of the rams. On applying the pressure water in the usual way the rams force the clamping sections inwards with a force which may exceed 200 tons, and whilst the commutator segments are held in this embrace the permanent clamps, insulating rings, etc., are put in position and tightened up.

The building up of the long commutators for turbo-dynamos, involving as it does the shrinking on of the steel clamping rings, offers additional mechanical problems for solution. Such a commutator in process of construction for one of Messrs. Brown, Boveri and Co.'s machines is shown in Fig. 139. The devices by which the copper and mica segments are being held together whilst the hot rings are slipped on can be made out by inspection. These rings, as above explained, are insulated from the copper of the commutator by mica, a substance that can stand high temperatures without melting. The process adopted by Messrs. Parsons and Co.,



Fig. 138.—Hydraulic Press for Commutators.

is to assemble the parts in massive clamps, and hold them together temporarily with steel binding wires. A mica insulating ring is then built up by slipping pieces of mica under rubber bands until a sufficient thickness is obtained; the rubber bands are then replaced by string. A red-hot steel ring is now slipped on, burning away the string, and in cooling grips the mica and the commutator so firmly that the former becomes practically solid.



Fig. 139.—Turbo-Commutator under Construction.

The commutator being the part of the machine most subjected to continuous wear, manufacturers have given some attention to making it interchangeable, so that when one commutator is worn out a duplicate may be ready to take its place with the least possible delay. Such a commutator as made by the Crocker-Wheeler Company for four-pole machines is shown in Fig. 140.* In

* Lent by the General Electric Company of London.

this case the hub upon which the commutator is built is designed to key, not on to the shaft, but on to a sleeve, which is an extension of the armature spider. The radial lugs for connecting the windings of the drum armature to the copper bars of the commutator are sweated and riveted



Fig. 140.—Interchangeable Commutator of Crocker-Wheeler Dynamos.

into the latter, for it is very essential that no solder should be used at the commutator bars, which may become heated by the friction of the brushes and by sparking. Should the temperature rise but moderately, the solder might be melted and the connectors loosened, whilst a still worse consequence would be the short-circuiting of consecutive bars with splashes of molten solder. At their outer ends the radial connectors are slotted to receive the ends of the armature coils, which are soldered into

the slots. These ends are not so liable to be over-heated or the solder melted.

Brushes and Brush-holders.—The life of a commutator depends to a great extent upon the kind of sliding connectors, the so-called brushes,

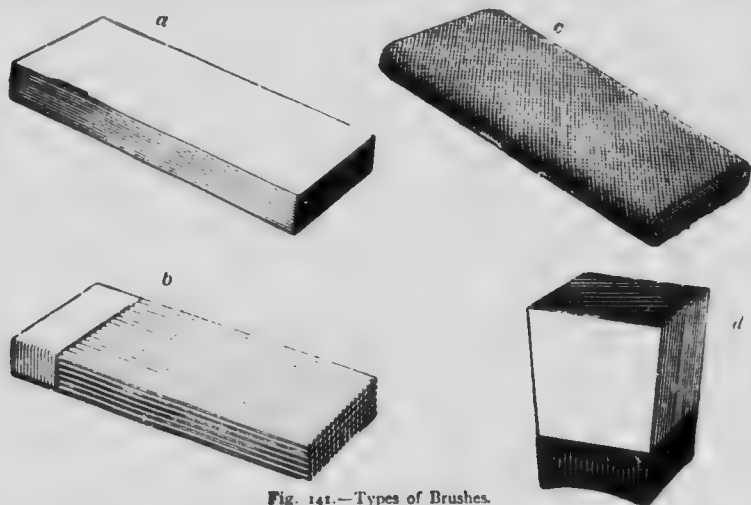


Fig. 141.—Types of Brushes.

used for drawing off the current, and upon the care and attention bestowed upon them whilst the machine is in use.

Brushes.—In the early days copper was the chief material used, but there was considerable variety in the form adopted. A certain amount

of flexibility is necessary on account of vibration and possible irregularities in the surface of the commutator. This flexibility was attained either by using sheets of copper (Fig. 141, *a*), or copper wires made into a bundle with a rectangular cross-section (Fig. 141, *b*). In both cases the separate parts must be firmly soldered at the end remote from the commutator, and enclosing clamps should be used close down to the working surface. Copper or brass wires are still considered by Messrs. C. H. Parsons

and Co. the best form of brush for high speed turbo-dynamos. Single stouter sheets of copper, slit longitudinally, were used in the Brush arc-light machine (see page 494, Vol. 1). Later (1885) Mr. A. P. Trotter suggested the use of wire gauze folded into a flat bundle (Fig. 141, *c*), the warp and woof of the gauze being placed diagonally to avoid the danger of loose pieces of wire being frayed out at the rubbing edges. Still later, Professor G. S. Forbes introduced the use of solid carbon blocks, (Fig. 141, *d*), which are now very widely used, as it has been found that the high specific resistance of the carbon assists the commutation by its effect on the time constant of the short-

circuited coil (see page 105). If properly adjusted, they wear down the commutator less, but they are liable to get hotter than copper, and should not be used on small commutators. The heating is increased considerably when the contact between the carbon and the metal of the brush holder is bad. The contact must be somewhat loose to avoid absolute rigidity at the rubbing surfaces; hence the difficulty, which is to some extent overcome by electrolytically coating the upper part of the carbon block with copper, which is sometimes nickelled or even gilded. A satisfactory way of meeting the difficulty is to bridge the loose joint with a flexible band of copper, rigidly attached to the

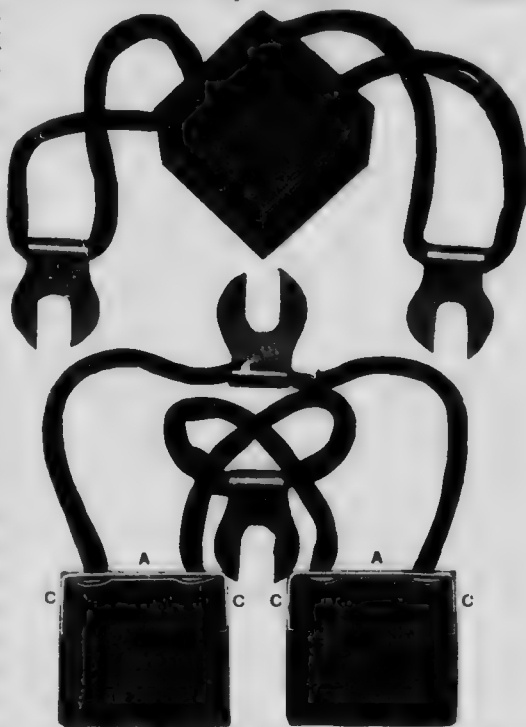


Fig. 142.—Carbon Brushes with Conducting Flexibles attached.

carbon and the metal of the holder, but even then there is a difficulty in getting good contact between the flexible and the carbon.

To provide for the numerous cases in which the design of the brush holder for carbon brushes does not ensure good electrical contact between the carbon and the fixed part of the holder, manufacturers of carbon brushes supply these brushes with flexible connections firmly attached to, and in good electrical contact with, the carbon, and such that the other ends of



Fig. 143.—The "Battersea" Connection for Flexibles.

these connections can be clamped to a fixed part of the holder. Examples of brushes provided with these flexibles are given in Fig. 142, which depicts brushes manufactured by the Morgan Crucible Company, Ltd., and intended more especially for turbodynamos. The top of the brush as shown clearly at AA is provided with a metal cap *c c* firmly embedded in the material of the brush. The flexibles pass through filleted holes in the top of the cap, and their ends are splayed out between the cap and a thin sheet of copper, good electrical contact being ensured by the great pressure used in the manufacturing process. No solder is used. The metal cap being spread over the top further ensures that the current shall be drawn equally from every part of the cross-section of the brush.

Another method, known as the "Battersea" connection, designed by the Morgan Crucible Company, to obtain good connection between the flexible and the carbon block, is shown in Fig. 143. Holes about half an inch deep are bored in the carbon, and the splayed ends of the copper wires of the flexible are introduced and clamped tightly by metallic powder consolidated by heavy pressure. Other methods of attaching the flexibles to the carbon blocks will be described in the section on motors.

It is somewhat important that some attention should be paid to the current density—that is, the amperes per square inch flowing from surface to surface at the commutator, and also flowing within the material of the brush. With carbon brushes the best practice provides a brush or brushes so long and wide that the current density does not exceed 35 amperes per square inch at the full load of the machine, and in no case should this density exceed 40 amperes per square inch. With copper the current density may be much higher, but there is no general rule, a frequent practice being to provide about one inch width of brush for every 100 amperes.

Another detail is the angle which the length of the brushes shall make

with the commutator. Copper sheet brushes may lie tangentially as at *a*, Fig. 144; wire or gauze brushes should make a more or less acute angle with the radius at the point of contact as at *b*, Fig. 144, so as to present the end and not the side of the brush to the commutator. Carbon brushes can be placed end-on or radially, as at *c*, Fig. 144, and as in this position the direction of rotation is a matter of indifference, it is adopted almost universally for traction and other motors whose direction of rotation has to be frequently reversed. Sometimes the carbon brush is set over as at *d*, Fig. 144, so that the revolving commutator may tend to push the brush against its supports and thus ensure better contact. In all these cases the direction of rotation of the commutator is supposed to be clockwise.

Brush Holders. — Besides holding the brush somewhat flexibly against the commutator, the brush holder has to conduct the current from the rubber or brush to the outer circuit. In addition it should be so designed that the brushes can be adjusted or removed for trimming whilst the machine is running, and it is well to have some arrangement for raising and holding the brushes off the commutator.

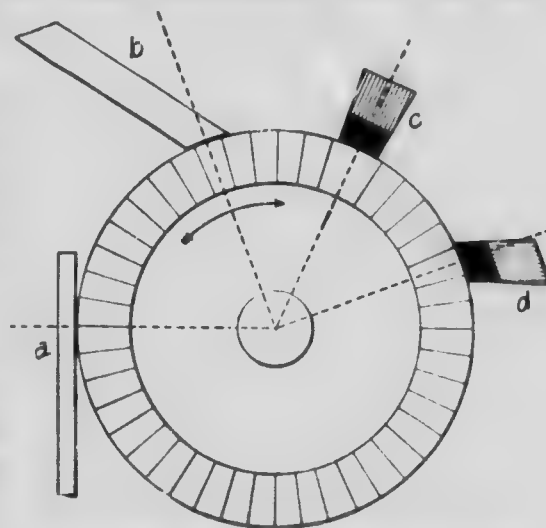


Fig. 144.—Different Angles at which Brushes may be Set on a Commutator

Since the brush holder is in the electric circuit, it must be well insulated from the frame of the machine and also from the brushes of opposite polarity. Except in machines which have a fixed position for the brushes—for instance, machines with interpoles and tramcar motors—the brush holders, both positive and negative, must be fixed on a movable rocker, so that they can be simultaneously moved round the commutator, and be placed in the best position for sparkless running as the load increases and decreases. The above points should be borne in mind in reading the following descriptions of actual brush holders.

A brush holder for carbon brushes, designed by the Crocker-Wheeler Company, is illustrated in Figs. 145 and 146,* the former being a side and the latter a perspective view. In this case the carbon block *B* is firmly

* Lent by the General Electric Company of London.

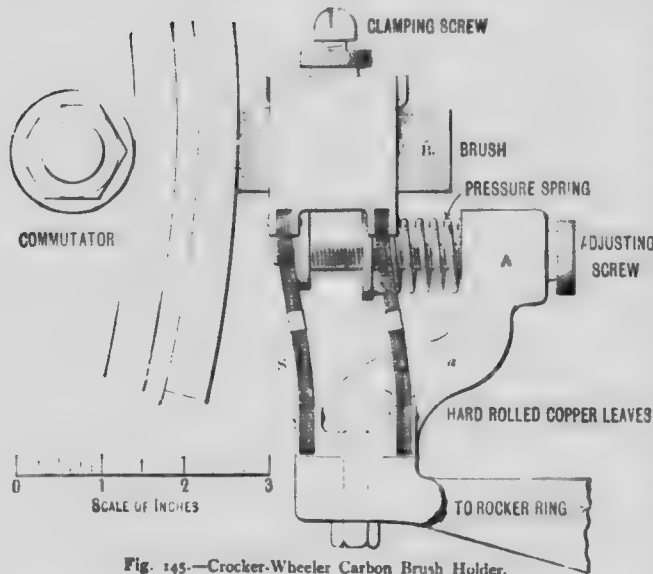


Fig. 145.—Crocker-Wheeler Carbon Brush Holder.

clamped in the cell *c* by two clamping screws which bear on a sheet of brass which protects the carbon from being broken by the ends of the screws. The cell *c* is carried by four flexible springs *s s*, one at each corner, formed of hard copper leaves, which are fixed at one end to the cell and at the other to the

solid base, which is in one piece with the spoke attached to the rocker ring. An adjusting screw passes through appropriate lugs on the cell *c* and loosely through the head *A* of a fixed arm *a*, between the lower surface of which and the upper lug on the cell *c* is placed the pressure spring. The whole design is ingenious, as it gives the necessary mechanical flexibility whilst providing a

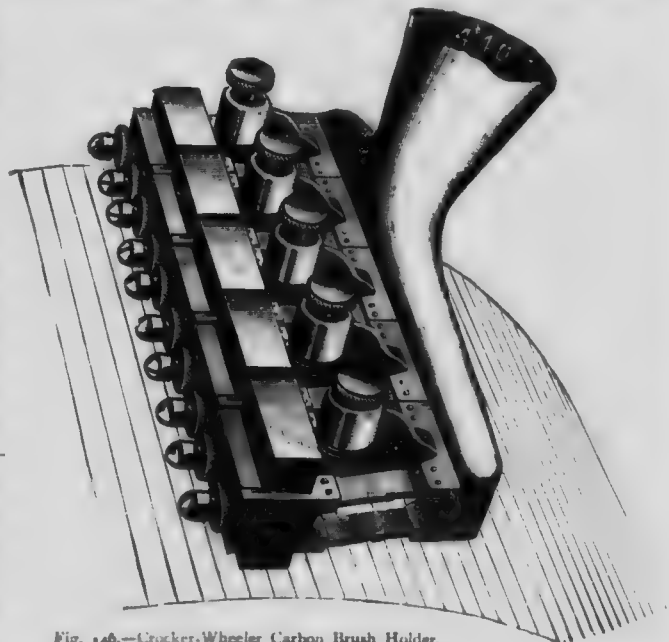


Fig. 146.—Crocker-Wheeler Carbon Brush Holder.

good conducting path between the moving brush and the fixed rocker through the copper leaves.

The brush holder used on the Johnson-Lundell generators is shown in Fig. 147. Here again the flexible mechanical connection, combined with

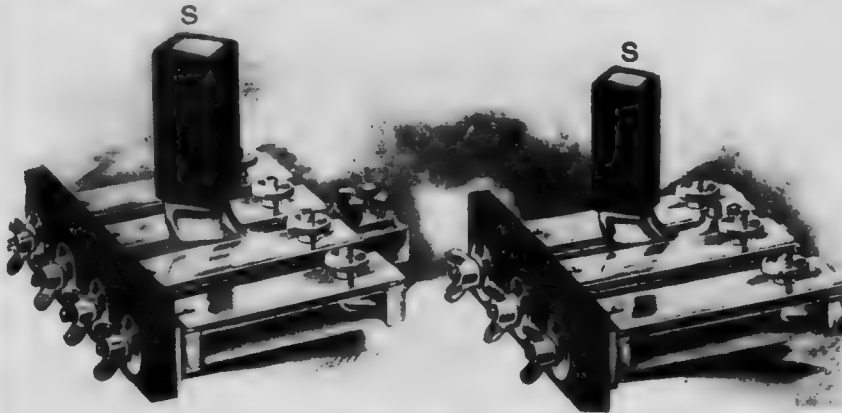


Fig. 147.—Johnson-Lundell Carbon Brush Holders.

good electrical conductivity between the brushes and the fixed part of the brush holder, is obtained by the use of long, flat springs, the details of which can be seen in the drawing. The carbon brushes are clamped on by butter-

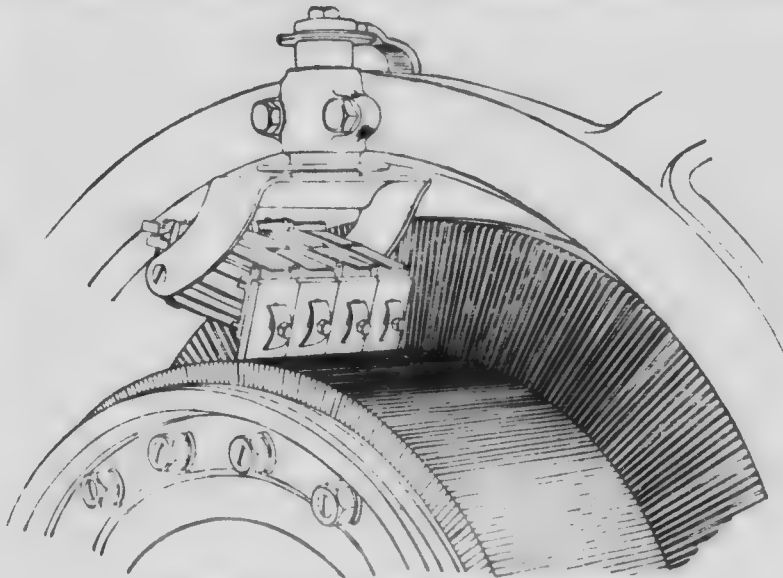


Fig. 148.—Dick, Kerr and Co.'s Carbon Brush Holders for Large Machines.

fly nuts and butt closely up against one another, in this way differing from the brushes which are clamped in separate cells. The advantage claimed for the arrangement is that it ensures an even wear on the surface of the commutator and prevents the development of ridges. The disadvantage is that it is not so easy a matter to remove one of a set of brushes whilst the machine is running. The stem *s*, to which the fixed part of the brush holder is attached, is shaped as shown so as to be conveniently clamped to the gear by which the brush holders are put in parallel and fixed to the machine.

The carefully designed brushes and brush holders used on the large machines built by Messrs. Dick, Kerr and Co. are shown in Figs. 148 and 149, the brush holders for their smaller machines being illustrated in Fig. 150. Fig. 148 shows in perspective the former gear attached to a 1,000-kilowatt machine, a brush holder for one of the brushes being shown in Fig. 149. These separate brush holders are threaded on to the spindle, which can be seen attached to the bracket in Fig.

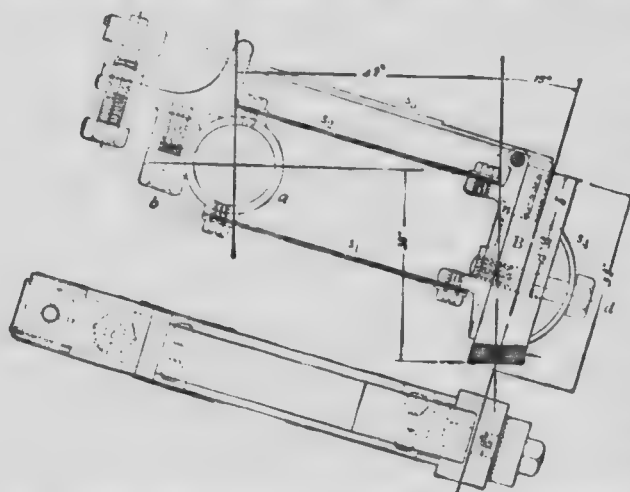


Fig. 149.—Details of Dick, Kerr and Co.'s Carbon Brush Holder for Large Machines.

148, this spindle being passed through the split sleeve *a*. Fig. 149, and firmly clamped at any convenient angle by the screw *b*. The brush carrier is borne by two long light springs *s*₁ and *s*₂ attached to the sleeve, and a longer and stronger spring *s*₃ attached to a bracket carried by the sleeve; this last spring can be adjusted by the screw *c*. The brush *B* itself is held firmly against the carrier *n* by the screw *d*, the head of which presses against a curved flat spring *s*₄, which presses on the surface of the brush, giving a firm but flexible grip. The whole arrangement is fairly simple and convenient, and is said to give satisfaction under very varied conditions.

For smaller machines Messrs. Dick, Kerr and Co. make the brush holder shown in Fig. 150. In this holder the carbon brush is carried in a cell which is cast in one piece with the sleeve *a*, which slips on to the brush spindle and is clamped tight in a fixed position by the screw *b*. The necessary flexibility is obtained by the movement of the carbon brush in

cell. The brush is pressed down on the commutator by the pressure of the curved arm *c* moving on the pin *p*. The pressure is regulated by the spiral spring *s* one end of which is fixed to the bracket; the other end is loose and is the lever *l*, which can engage in any one of the notches of the semicircular toothed sector *d*, thus setting up or slacking off the force of the spring and adjusting the pressure on the brush. As the brush is loose in its cell, electrical connection has to be made between it and the fixed sleeve by the flexible conducting cord *v*. The design is good, simple, and not costly to manufacture.

Two patterns of radial brush holders, designed by Mr. Churchward, of the Siemens and Halske Company of America, for the large multipolar generators of the company, are shown in Fig. 151. The carbon block is fitted into a three-sided metal box, which slides inside another metal box attached to the fixed part of the holder. A pin projects from the back of the first box sufficiently far for a flexible lead to be soldered to it. Surrounding this pin, but separated from it by a badly-conducting sleeve to keep it from being heated, is a spiral spring, by

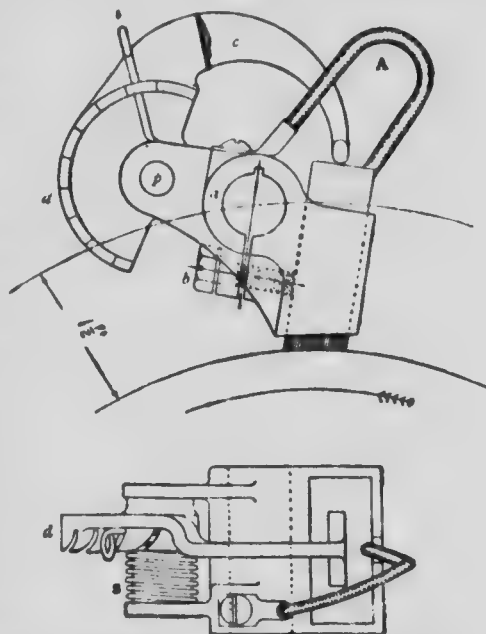


Fig. 150.—Dick, Kerr and Co.'s Carbon Brush Holder for Small Machines.

which the pressure of the carbon against the commutator can be readily adjusted. The protection of this spring from being heated ensures that its elasticity will be retained for a much longer period than if it were being continually heated and cooled. It is claimed that the brushes can be relied upon to be self-feeding and self-adjusting.

The high speed at which turbodynamos run, combined with the vibration of the shaft, renders it difficult to ensure a firm contact of the brush

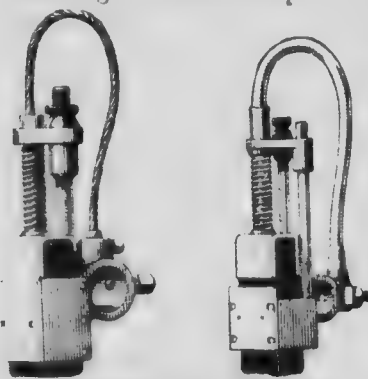


Fig. 151.—Siemens Carbon Brush Holders.

without excessive pressure, and, therefore, excessive friction, leading to large development of heat. Devices for cooling the commutator are described elsewhere, as well as the use of radial brushes which are not affected by the vibration or chattering of the shaft. Fig. 152 shows a plan which has been worked out by the Morgan Crucible Company, Limited, to give an elastic pressure which will respond more rapidly to the vibrations than metallic

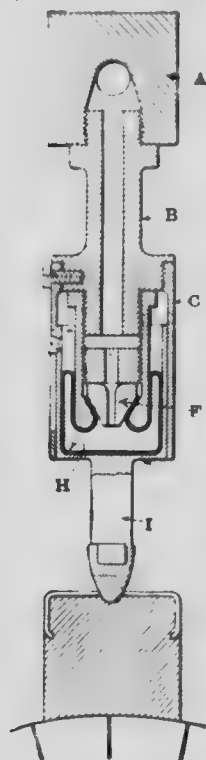


Fig. 152.—Details of Pneumatic Brush for Turbo-Dynamos.

dynamo, a few strokes at starting being sufficient to set up the pressure. Two pumps are used, half of the brushes being placed on each to provide against the contingency of the air pressure being accidentally destroyed. As it would be improbable for this to happen to both pump systems simultaneously, only half the brushes would be placed *hors de combat* at any one time by such an accident.

Brush Gear and Brush Rigging.—It will be interesting to consider next the methods by which the brushes and their holders are mounted on the machines with or without provision for rocking.

springs can. The principle consists in the substitution of compressed air for a solid spring. The compressed air entering the chamber in the nut A, passes down the core of the stem B, through the nozzle F, into the chamber H. The stem I, carrying the carbon brush, is firmly attached to the hollow cylinder, which slides inside the outer cylinder C, the air being prevented from escaping by the flexible packing. The result is that the compressed air in the chamber acts as an elastic cushion, and maintains the brush in close contact with the commutator without excessive friction.

For actual use the brushes and holders are assembled, as indicated in Fig. 153, which shows a brush spindle and eight brushes in position on the commutator of a turbo-dynamo. Full details of the mounting, which is most conveniently described here, instead of later, are given in Fig. 154, in which will be seen how the carbon brushes are supported by collectors separately from the pneumatic gear, which is used solely to supply the necessary pressure at the back of the carbon block. Details of the rocking arrangement for adjusting the lead of the brushes can be readily made out, the rocker being locked by the handles H H when the right position has been found. The sectioned block B represents the bar conveying to the chamber behind the plunger the compressed air, which is supplied at a pressure of 2 lbs. or 3 lbs. per square inch by two small pumps placed on the bed-plate of the

The brush gear used by Messrs. Crompton and Co. for their machines is shown complete and also dissected in Fig. 155. The split

holder, which is clamped to a suitable seating on the bearing hood, is shown at R. It has diametrically opposite positions projecting lugs to which are attached the brush spindles, which are insulated from the metal of the machine by a mica collar C. The brush spindles carry the brush holders R, which are of the

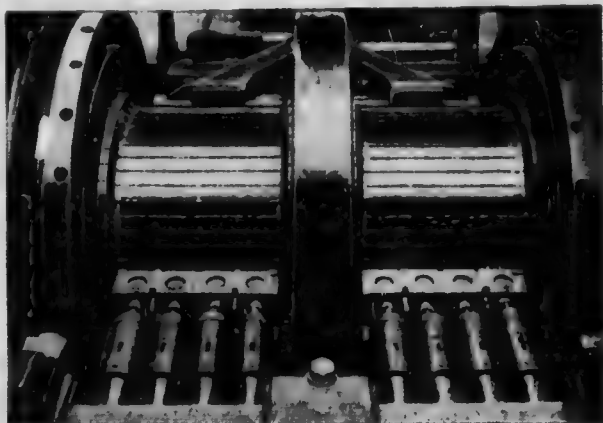


Fig. 153—Pneumatic Brushes in use.

box type for carbon brushes, are fitted with adjustable springs, and are mounted so as to permit of a radial adjustment of the box to allow for

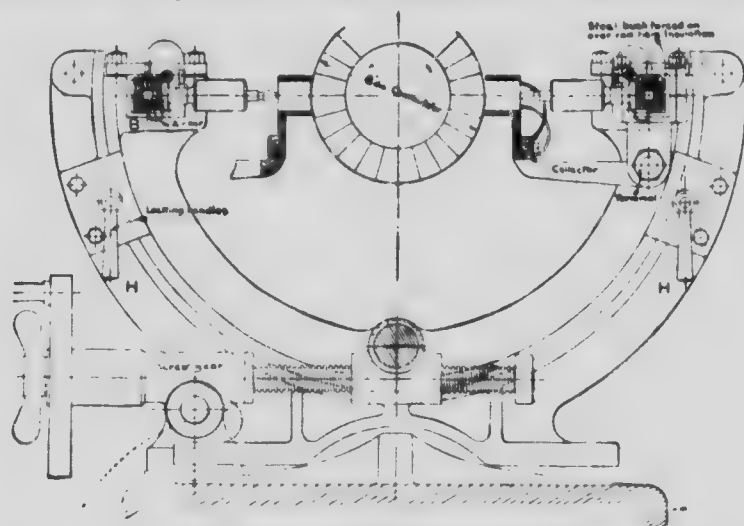


Fig. 154.—Detail of Rigging for Pneumatic Brushes.

to wear of the commutator. The current is transmitted from the brushes to the spindles by flexible copper connections, thus bridging the loose contact. The brush spindle is prevented from turning round by

the locking plate *L*, to which it is keyed, one end of this plate being registered by a pin in the rocker, from which it is insulated by the collar *F*. The washers *W* are fitted between the nuts and the insulating collar *C* on the spindle. A six-pole 50-kilowatt machine showing brush gear of the above pattern in position is illustrated in Fig. 156.

The collection of the large currents at low voltage, generated by comparatively small machines for electrolytic work, requires careful design in the commutator brush holders and brushes. The commutator is much

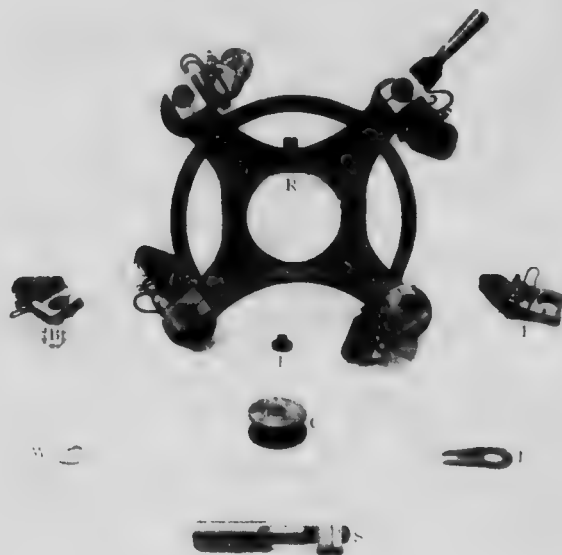


Fig. 155.—Details of Crompton Brush Gear.

longer than commutators on machines of equal output at higher voltages running at approximately the same speeds, and, as a rule, the commutator bars are much thicker and fewer in number. The brushes are, of course, more numerous, since it is more convenient to have a number of comparatively narrow brushes than one or two abnormally wide ones.

In the early days machines for electrolytic work were bipolar, and some such have been described in previous editions. This necessitated the collection of the whole of the current by a single line of brushes, but in view of the low voltages required such machines can well be made multipolar with comparatively small diameters of the armatures, and with fairly low speeds. By using the multipolar principle the collection of the current becomes easier, as it is divided between a greater number of brush spindles, and at the low voltage there is practically no danger of "flashing over," even though the brushes of opposite polarity are comparatively close together on the commutator.

The brush gear of a six-pole machine designed by Messrs. Crompton and Co., Limited, specially for electrolytic work is shown in Fig. 157.

The dynamo being driven by an electric motor, shown on the right, taking power at a much higher voltage. The dynamo when run at 600 R. P. M. is capable of giving 3,000 amperes at from 2 to 8 volts. It is not self-excited, for since the higher voltage supply is available it is found preferable to take the excitation current from it, as excitation at the above-named low voltage would necessitate heavy windings on the magnet circuits. In this case, by

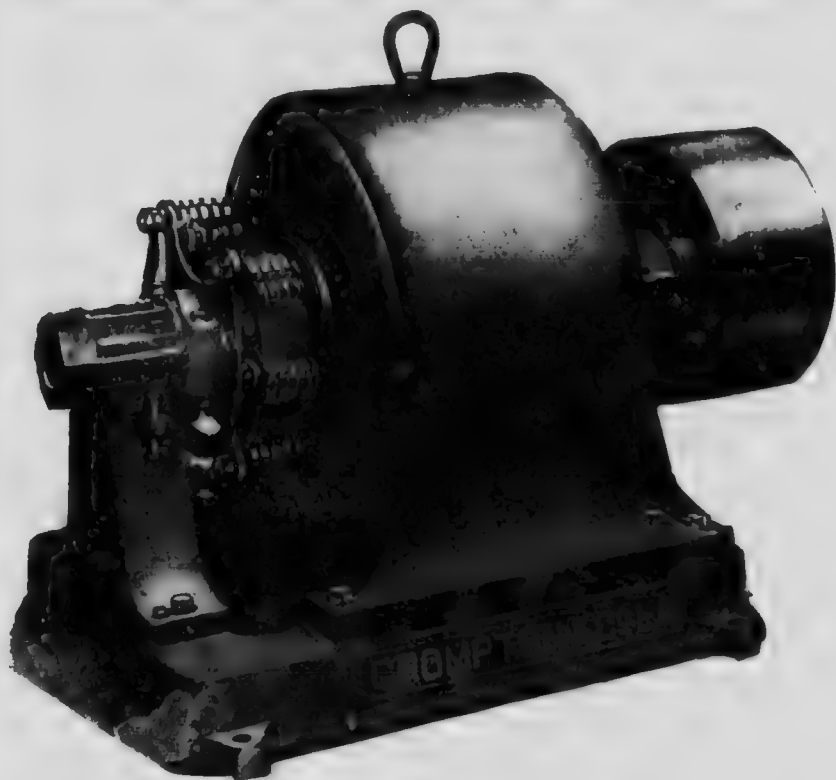
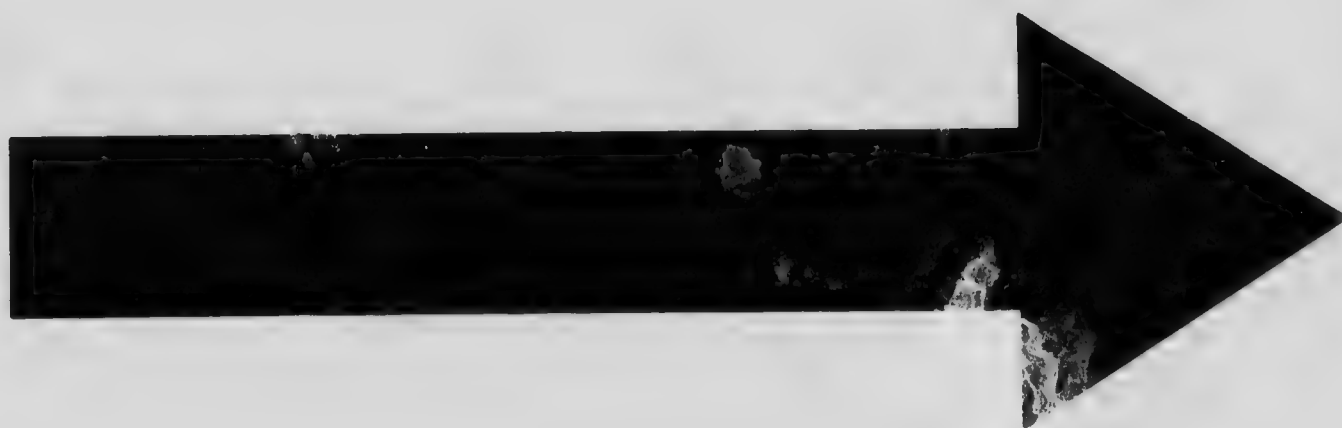


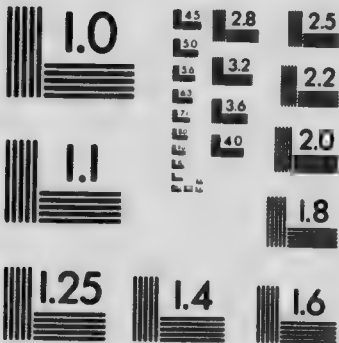
Fig. 156.—Crompton 50-Kilowatt Dynamo, showing Brush Gear.

using the 460 volts of the supply circuit rather than the two to eight volts of the machine itself, the exciting current, which has to supply 4,500 ampere-turns per pole, is reduced from between 100 and 400 amperes to the low figure of 1.75 amperes for which the magnet coils can be more easily wound. Further advantages are that the difficulty of having to handle these additional currents on the commutator is avoided, and also the still greater difficulty of adjusting such heavy currents for varying loads and voltages. The power used for excitation is 800 watts, which is only 3.3 per cent. of the full-load, 24 kilowatts, of the machine. The mount-



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ing of the brush gear is of the usual "Crompton" type already described (see page 155).

In large machines for electrolytic work it is not unusual to find the current divided between two wide commutators, one at each end of the armature, thus giving a longer axial bearing surface for the brushes without inconveniently lengthening the pins upon which the separate brushes are threaded.

Brush Gear for Large Machines.—For large multipolar machines something more is wanted than the simple rocker of the bipolar machine on which

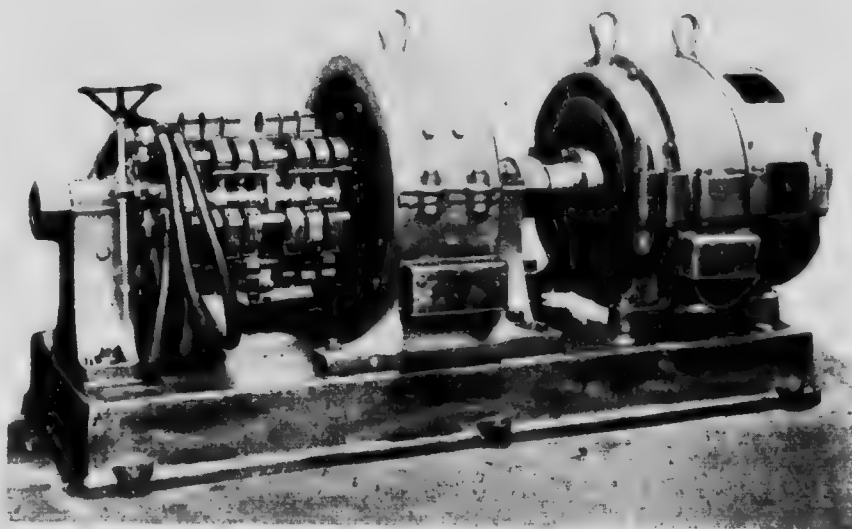


Fig. 157.—Brush Gear on Crompton 3,000-Ampere Low-Voltage Dynamo.

the two brush holders of such machines are usually mounted. In the early days of multipolar machines, schemes of winding the armature were devised such that all the necessary cross-connections were made inside the machine, and the number of brush holders, reduced to two, placed at an angular distance apart depending on the number of poles. Such windings, though possible, are not now widely used in practice, chiefly because of their complexity, which not only increases the danger of error in construction, but also makes repairs costly in the event of a breakdown. Passing by series and series-parallel winding schemes, there are, except for balancing purposes, already referred to (see page 128), no cross-connections inside modern multipolar machines, and the necessary paralleling of the different sections of the armature is accomplished by connecting the brushes in two sets with

proper conductors, which are carefully designed as part of the brush gear. The result is that the arrangements for carrying the brush holders and properly connecting them to one another and the terminals, and for enabling them to be rocked simultaneously to adjust the lead, cause a very serious addition to the prime cost of the machine, and also necessitate more constant supervision and care from those who are in charge of it when in use.

The complexity of the brush gear, including the brush holders as a

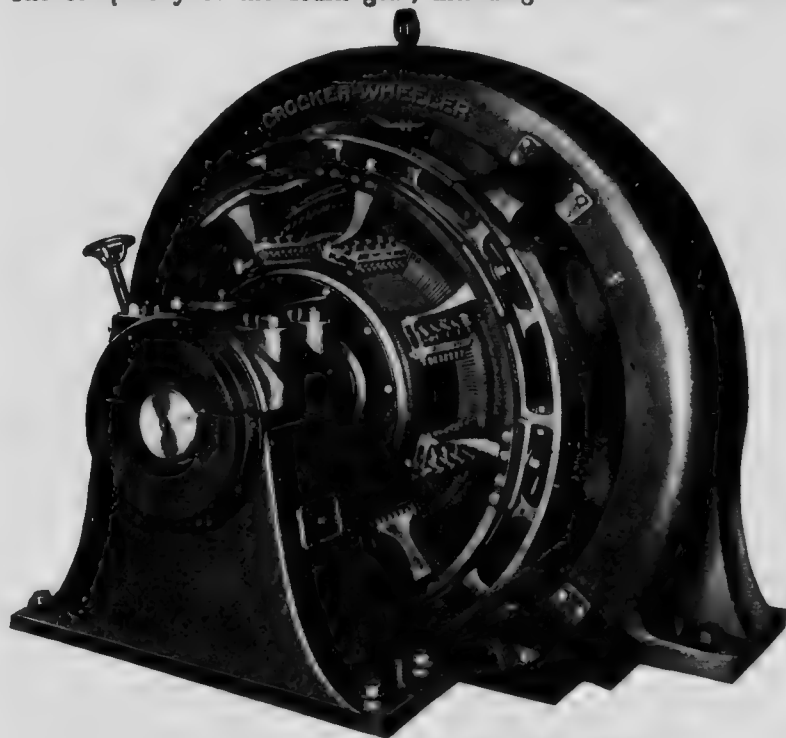


Fig. 158.—Mounting of Brush Gear on Crocker-Wheeler Dynamo.

part thereof, increases with the number of poles and the magnitude of the current to be collected, and this complexity, combined with the actual weight to be supported and the stresses to be provided for, has led to various methods being adopted for the main support of the brush gear. For our present purpose it will be sufficient to divide these into *three classes*, and to refer briefly to each. The classes are those in which the gear is carried (a) by the magnet frame of the dynamo, or (b) by the pedestal containing the axle bearing, or (c) by a separate support bolted to or otherwise carried by the bed-plate.

(a) *Magnet-supported Brush Rigging.*—Several examples of the first of

the above classes are given in different parts of the book, and a further example is given in Fig. 158, which shows the mounting of the brush gear of a large eight-pole Crocker-Wheeler dynamo. The gear is supported from the yoke ring of the machine by four projecting brackets bolted on to the latter. These brackets encircle an outer iron ring with a kind of half sleeve, through which the ring can slip when the worm gear, operated by the hand wheel H, is worked. The brush rigging of a similar machine, but generating still heavier currents, is shown separately

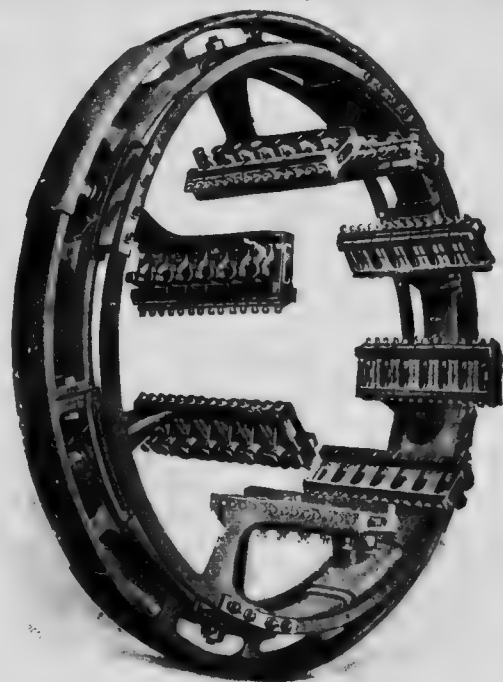


Fig. 159.—Brush Rigging of 1,500-Ampere Crocker-Wheeler Dynamos.

The dynamo in Fig. 158 has an output of 150 kilowatts at a speed of 150 R. P. M., the voltage being 100, which gives a current of 1,500 amperes, or 375 amperes per brush holder, and as each brush holder contains four carbon brushes, there is an average current at full load of about 94 amperes per brush. The brush gear shown in Fig. 159 would at the same density carry about 2,600 amperes. As an instance of careful attention to small details, it may be noted that the copper rings between the brush attachments are overwound with cord covered with insulating paint.

It will be instructive for the reader to compare this brush gear with the brush gear shown in Fig. 203, depicting a more recent machine by the

in Fig. 159. A circular iron casting, made in two parts, supports the brush holders, which have already been partly illustrated in Fig. 146. The holders are, of course, insulated from the iron rings to which they are mechanically attached by iron brackets. Two flat copper rings are attached, one on either side of the inner rocker ring, all the + brush holders being electrically connected to one of these rings, and all the — brush holders to the other. The attachment of the rigging to the yoking ring is shown in Fig. 158,

same firm. The later machine collects 3,750 amperes with six brush spindles and thirteen brushes per spindle, which works out to 48 amperes per brush holder.

Another example, this time of English design, is given in Fig. 160, which represents a ten-pole dynamo built by Messrs. Dick, Kerr and Co., Limited, in which the brush rigging is also carried by brackets attached to the yoke ring. In this case the brackets only encircle sectors of a ring, and these sectors support a continuous ring of much smaller diameter, to

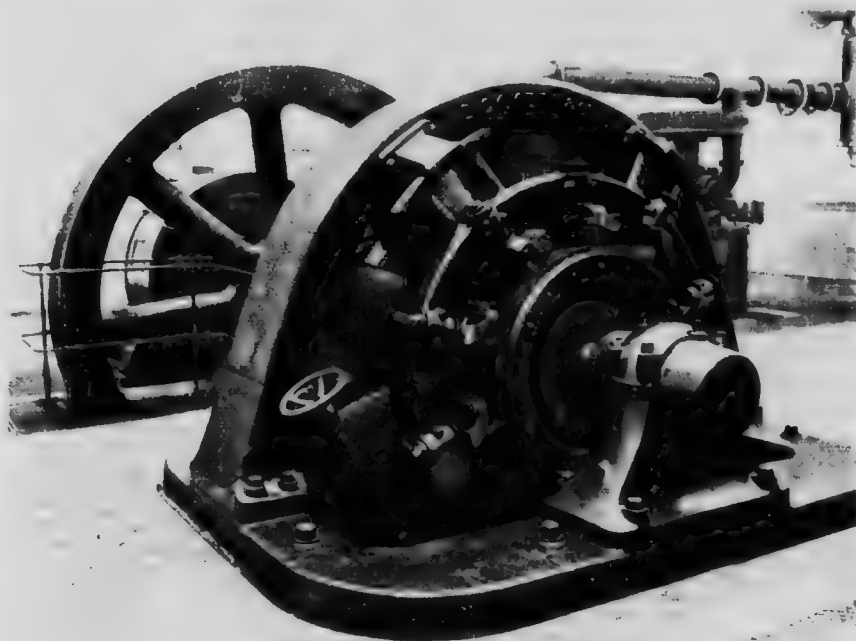


Fig. 160.—Mounting of Brush Rigging on Dick, Kerr Dynamo.

which the brush spindles are attached. These spindles carry brush holders of the firm's standard type, which has already been described (see page 152). The machine not having commutating poles, arrangements are made to rock the whole of the brush rigging in the usual way, the sectors sliding in the bracket attached to the yoke ring being sufficiently long to provide for the full range of movement which is likely to be required. The machine illustrated, which was supplied to the well-known Atlas Works of Messrs. J. Brown and Co., at Sheffield, has a full-load output of 1,630 amperes at 230 volts, or 375 kilowatts when running at 140 R. P. M.

Similar methods for supporting the brushes are used by the Brush

Electrical Engineering Company, as will be realised by an inspection of Fig. 161, which depicts a machine having an output of 500 kilowatts at 500 volts when run at 500 R. P. M. There are, however, important differences in the details of the design of the fixed supporting brackets, the movable ring, and the arms by which the actual brush holders are attached to the movable ring. The reader will find it interesting to compare Figs. 161 and 160 point by point. The full load current is 1,000 amperes, which gives 200 amperes for each of the brush spindles. The $+$ and $-$ paralleling rings are well protected by the movable ring. There is the usual

rocking gear for a non-interpole machine.

Particulars of a similar method adopted by the International Electrical Engineering Company of Liège are given in section in Fig. 162, which is taken from the dynamo already partly described at page 110 (Fig. 95). The bracket B supporting the ring R is attached to F, which is part of the frame of the machine, and the

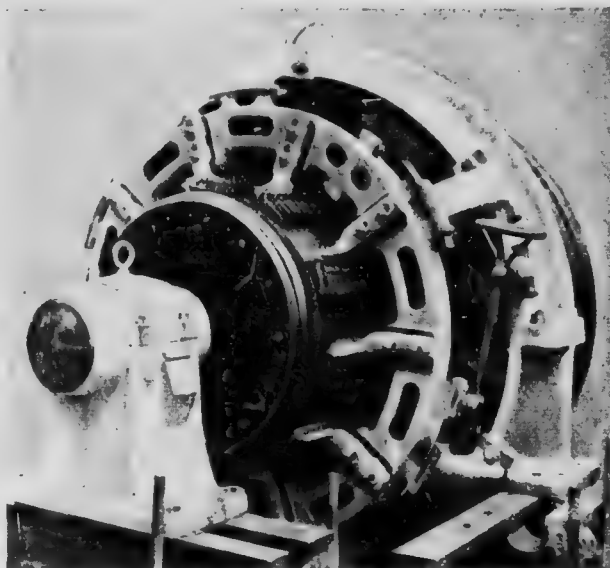


Fig. 161.—Mounting of Brush Rigging on a Brush Electrical Engineering Company's Dynamo.

Brush spindles *s* are carried on the ring in the manner shown. Incidentally, the illustration gives interesting details of how the commutator *c* is built up and supported from the armature spider *P*.

As a final example of this type of mounting we illustrate in Fig. 163 the substantial brush gear attached to a dynamo built by the Westinghouse Company, and intended for electrolytic work, to give the large current of 4,250 amperes at 200 volts when running at 80 R. P. M. The machine has 16 poles and the same number of separate brush spindles. At full load each of these brush spindles will have passing through it a current of 530 amperes, which is divided between eight separate brushes, or an average of 66 amperes per brush, which certainly does not err on the side of being too small, and yet even this current per brush necessitates no less than 128

separate brushes. These figures give some idea of the difficulties to be faced in designing the multipolar brush gear for currents of this magnitude.

The sixteen brush holders are supported by a broad, flat ring, which is carried by lugs projecting inwards from a ring which appears to be bolted to the yoke ring. The rings *a* and *b* for joining alternate brushes in parallel are slightly larger in diameter, and lie one in front of the other with insulating distance and carrying pieces at intervals; projections from the very substantial brackets which carry the brush holders are bolted to these rings, as shown. The whole is so mounted that it can be rocked to adjust the lead by means of the hand wheel on the right-hand side. This hand wheel, through the bevel gear, rotates the horizontal shaft at the bottom, and this shaft carries a worm which works into the worm teeth on the short circular segment attached to the rings at the bottom. One great advantage of this design is that the rings do not project over the commutator face, and therefore the numerous brushes and the commutator itself can easily be inspected whilst running and kept in good order by the attendants.

(b) *Pedestal-supported Brush Rigging.*—Examples of the second method of supporting the brush gear, namely, from the pedestal carrying the axle bearing, have appeared on several machines already described (see Figs. 5, 6, 12, 123,

156, 157 and Plate III.), and a fairly simple example is exhibited in Fig. 164, which is taken from a six-pole machine, having an output of 75 kilowatts, and constructed by the International Electrical Engineering Company of Liège. The rocker is a six-arm spider moved and clamped by the handle *H*. The projecting arms carry the insulated pins *p* which support the brush holders, and these pins are connected three and three by two substantial copper straps, one of which passes outside and the other inside the arms of the spider. The connecting washers on these straps are extended at the two lowermost

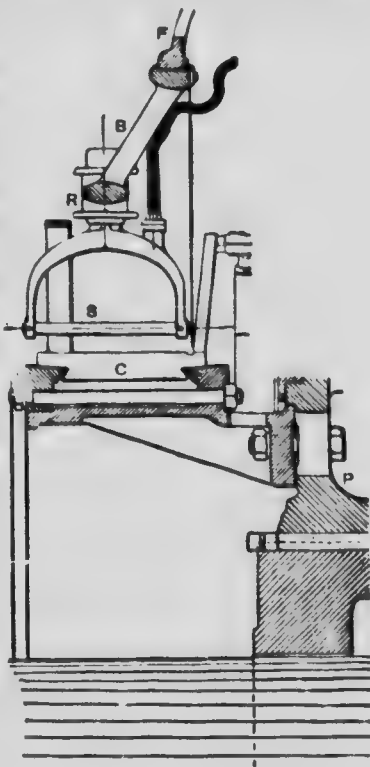


Fig. 162.—Details of Brush Rigging of Liège Dynamo.

brushes into thimbles into which are sweated the flexible conductors connecting the rings to the terminals. The machine is designed to give 312 amperes at 240 volts ; there are therefore 104 amperes per brush holder, and



Fig. 163.—Brush Gear of 4,250-Ampere Westinghouse Dynamo.

this current is collected by three carbon brushes in each holder. A more recent example of such a method of support is given in Fig. 165, which depicts a much larger machine built by the Electrical Company, Limited, and designed

to give 960 amperes at 230 volts when run at a speed of 425 R. P. M. The machine being a ten-pole dynamo, the brushes are carried on a ten-arm spider, each arm carrying at its extremity one of the insulated brush spindles, which in its turn carries seven brush-holders and their brushes. Each brush therefore collects 27.5 amperes and each spindle 192 amperes. As in the last example the paralleling rings *a* and *b* are carried by the positive and negative brush spindles respectively, one, *a*, outside the spider arms and the other, *b*, inside. The hand-wheel for rocking the spider, and through it the brushes, is shown, and the method of operation can be readily made out. The usual rocking arrangement is shown, although the machine has interpoles:



Fig. 164.—Brush Gear of Six-pole 75-Kilowatt Dynamo.

Another example is the large ten-pole dynamo of which full details are given in Plate III. and which has already been partly described elsewhere (see pages 22 and 85).

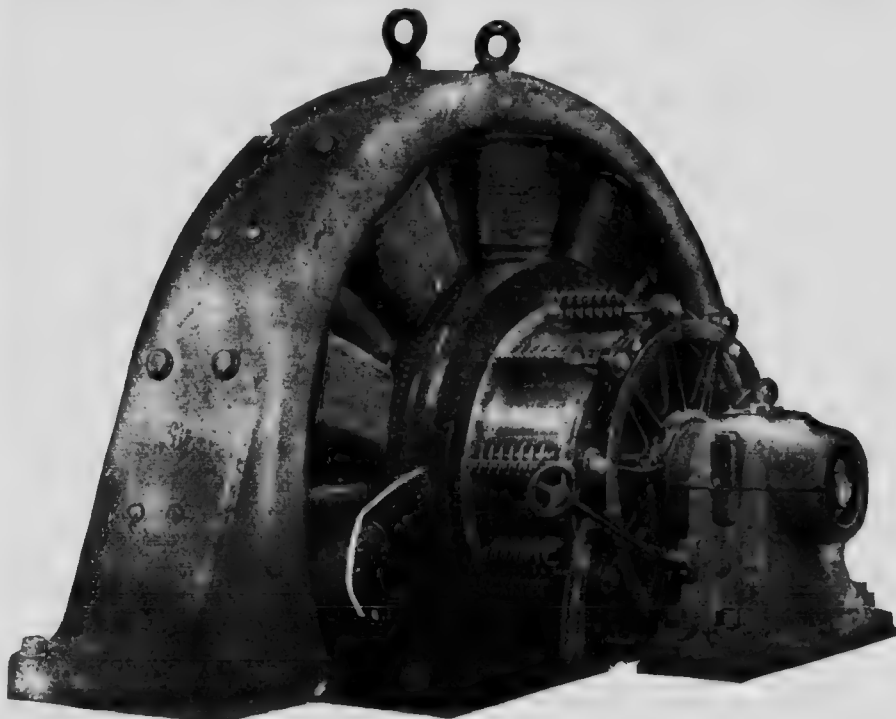


Fig. 165.—Mounting of Brush Gear on Ten-pole 220-Kilowatt Dynamo.

There are 10 collecting spindles each mounted on one arm of a ten-arm spider, and each carrying 12 carbon brushes. Since the full load current is 1,650 amperes, the current per brush is about 27.5 amperes, and the total number of brushes is 120. The commutator is 30" in diameter, and at the normal speed of the machine, 250 R. P. M., run at a peripheral speed of 1,970 feet per minute. It is interesting to note that the paralleling rings are both on the bearing side of the spider, and

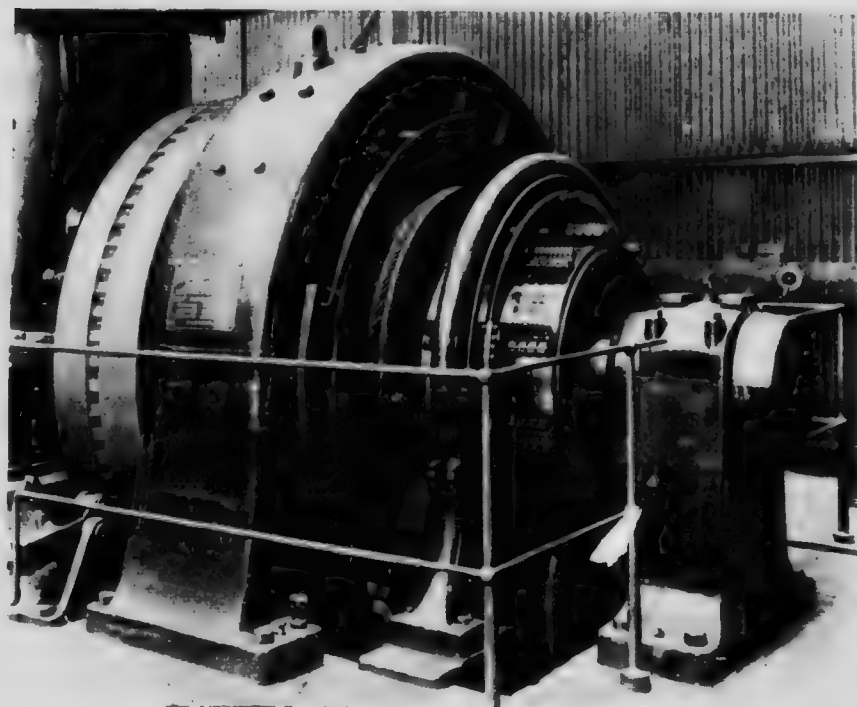


Fig. 166.—Mounting of Brush Rigging on 1,800-Kilowatt Siemens Dynamo.

that there is no arrangement for rocking the brushes, the commutating poles enabling the machine to run with fixed brushes, the position being determined once for all and for all loads when the machine is first tested. To diminish the actual current in the different parts of the paralleling rings the cables to the fixed terminals are attached to more than one spindle in each ring.

(c) *Separately Supported Brush Rigging.*—An example of the last division of our classification, in which the brush gear is supported separately from the machine itself, is given in Fig. 166, which represents a large multipolar dynamo built by Messrs. Siemens Brothers Dynamo

Works, Limited, and designed to give 1,800 kilowatts at 530 volts when running at 230 R. P. M. This means that the current to be collected is about 3,400 amperes. As will be seen in the illustration, the main support of the brush rigging is a substantial ring carried by two brackets separately bolted to the foundations. This ring encircles the commutator at about the middle of its axial length, and from it the brush spindles extend right and left over the surface of the commutator carrying brush holders of the pattern already described (Fig. 151), as designed by this firm. As the machine has ten poles there are ten collecting spindles, and there appear to be five brush holders on each visible half spindle. This gives the some-



Fig. 167.—Turbo-Dynamo Brush Gear for Metallic Brushes.

what large current of 68 amperes per brush holder. One of the paralleling rings joining alternate brush spindles, as also its connections to the brush spindles, can be clearly seen, as also can one of the leads passing away from this ring into the pit or tunnel below the dynamo through which, as is usual in machines of this size, the current generated is led away to the switch-board.

The most numerous examples of this method of supporting the brush rigging occur in the design of turbo-dynamos, which will now be dealt with separately as they have been in other parts of the book.

Brush Gear for Turbo-Dynamos.—In the early days of the development of turbo-dynamos the advantages of using carbon brushes were not so well understood as they were subsequently; and moreover there were, and still are, difficulties in their use, to which allusion has been made else-

where. Consequently the brush gear was designed for the use of wire gauze or wire brushes, and some designers still hold that such brushes, especially when combined with a grooved commutator, are best for this particular work.

A turbo-dynamo commutator with brush gear for metallic brushes is shown in Fig. 167. The machine is obviously bipolar and, except for the massiveness of the mounting and the presence of the clamping rings, the figure might belong to an ordinary dynamo for electrolytic work. Attention may be drawn to the thickness of the commutator bars, which can be clearly seen, as the photograph has been taken with the machine not running.

With the development of the turbo-dynamo during the last few years special attention has been paid to all the details of the brushes and brush

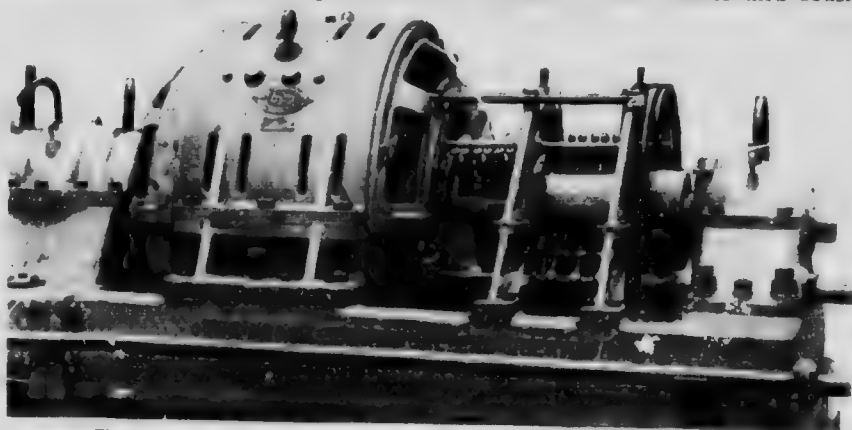


Fig. 168.—Brush Rigging of Brush Electrical Engineering Company's Turbo-Dynamo.

rigging, upon which in no small measure successful and sparkless running depends. A few examples will be interesting as showing the solutions arrived at by various well-known firms.

The brush rigging used by the Brush Electrical Engineering Company on a 600-kilowatt machine running at 2,100 R. P. M. is shown in Fig. 168. There is one median clamping ring on the commutator, and the rigging is supported at the armature end from the frame of the machine, and at the bearing and the intermediate positions by two special ring brackets bolted to the bed-plate and spanning over the commutator. The rings are stayed by special struts at the top, besides being maintained at their proper distance apart by the brush spindles. The full load output at 500 volts is 1,200 amperes, and as the machine is four-pole, each line of brushes has to deal with 600 amperes. Carbon brushes are used having low friction loss and low contact resistance.

The most recent form of brush rigging used? Messrs. Brown, Boveri

and Co., for large machines, is shown in Fig. 169, which depicts the brush rigging used in a 1,000-kilowatt turbo-dynamo capable of giving out at of 1,400 amperes at 750 volts when running at 1,500 R. P. M. The machine is four-pole, and the two necessary collecting rings are hidden by the end shield, but the two substantial terminals, by which the above heavy current is led out, can be seen projecting from the shield. The brush holders on each spindle are in three groups of four each for a commutator similar to that shown in Plate IV., which, however, is for a heavier current at a lower voltage. In Fig. 169 each brush will be carrying nearly 60 amperes at full load. The attachment of the brush rigging to the machine can be well seen in Fig. 170, which shows a six-pole Brown, Boveri set giving 2,170 amperes at 230 volts or 500 kilowatts at 1,750 R. P. M. Here again each brush collects about 60 amperes, and there are 720 amperes per spindle, but it will be noticed that there is only one clamping ring on the commutator. There is no arrangement for rocking the brushes, as the machine is designed to run at all loads, up to 20 per cent. overload with the brushes in a fixed position. Attention may also be called to the separate ex-

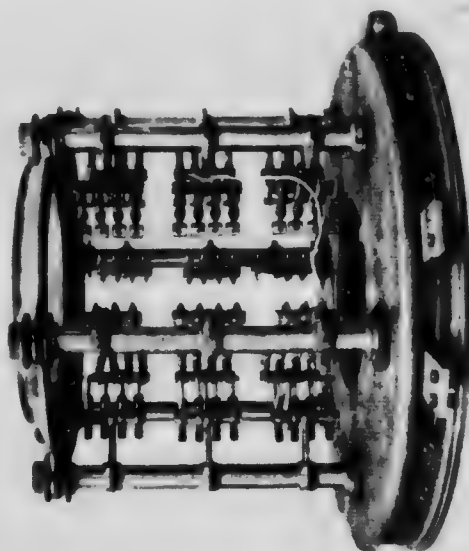


Fig. 169.—Brush Rigging for Brown, Boveri and Co.'s Turbo Dynamos.

iting dynamo carried on a bracket by the end pedestal. The necessity for such an addition is alluded to elsewhere (see page 116).

The brush rigging used by the Westinghouse Company for their radial commutator dynamos is shown in Fig. 171, which depicts gear frame, brushes, and rocking gear for a 750-kilowatt four-pole machine. It will be remembered (see page 142) that in this type of commutator the brushes press sideways on projecting portions of the commutator bars, thus avoiding the disturbance due to the chattering of the shaft, and being only affected by its movement in the direction of its length; as this movement is comparatively slow and of long period it can be readily followed by the brushes. A similar brush rigging attached to a somewhat smaller (500 K. W.) machine running at 2,500 R. P. M. is shown in Fig. 172 in which the radial bars of the commutator

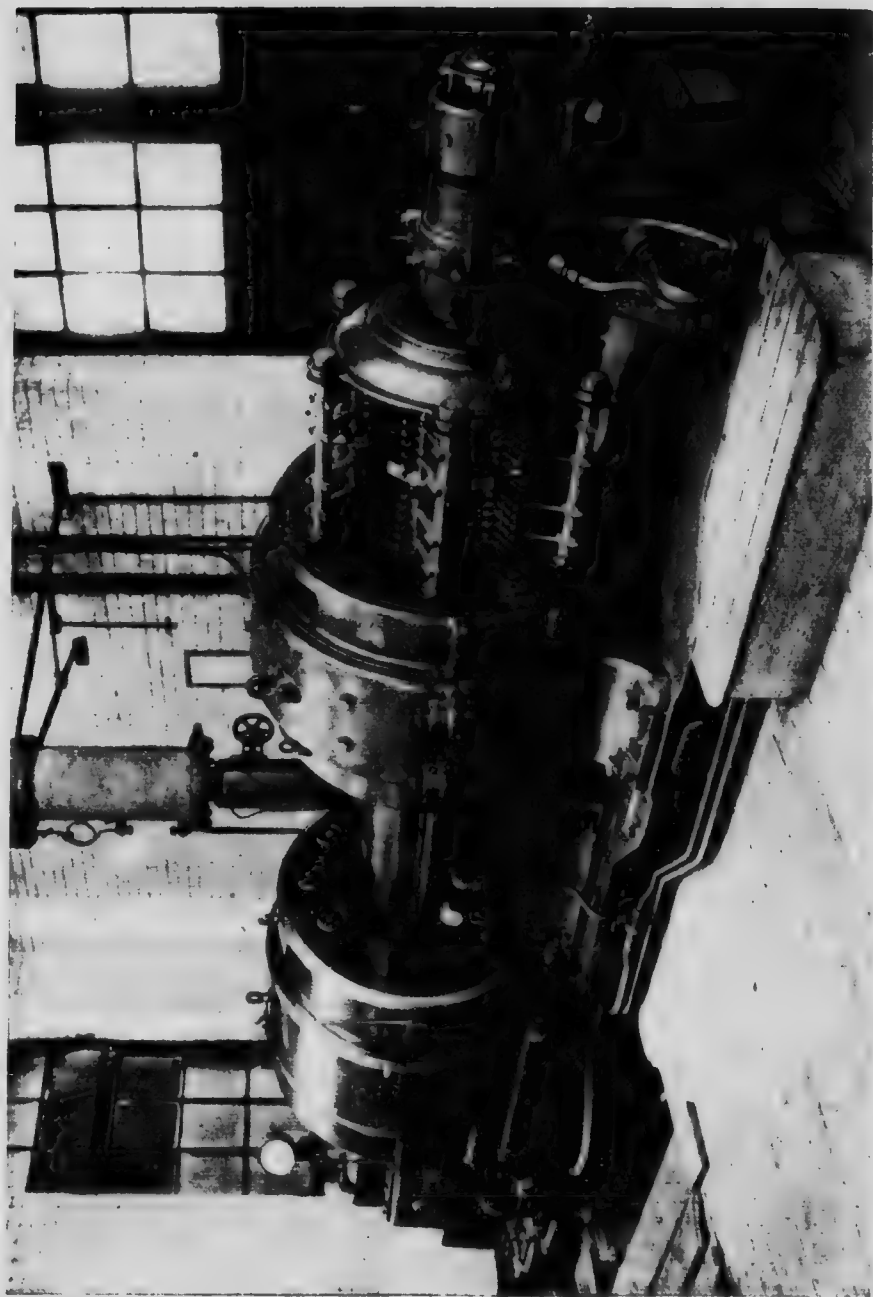


FIG. 17. Brown B. & Co. Six Pole Turb. Jan. 1911. Set. 100. 1750 R. P. M.

can be clearly seen. The springs which give the necessary elasticity to the pressure of the brushes are placed between the two brushes of each pair, and can be set up and adjusted by the pins which can be seen projecting in Fig. 172. The way in which such an arrangement adapts itself to the endwise play of the shaft is obvious. The details of the rocking gear can probably be made out better in Fig. 172 than in Fig. 171. The brushes in Fig. 172 collect 1,250 amperes at 400 volts. Each pair of brushes therefore averages 125 amperes or 62.5 amperes per brush. It will be noticed that the brush rigging is supported independently of the machine, and therefore falls into the third division of our classification. The complete machine is shown in Fig. 173.

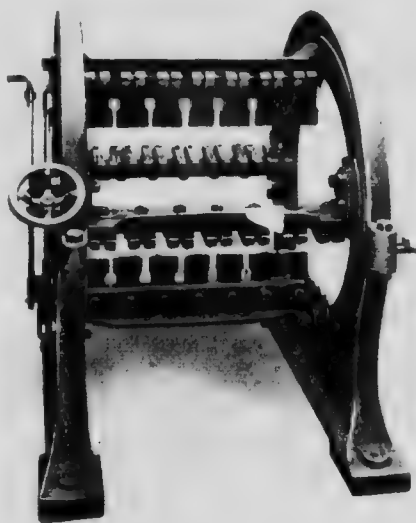


Fig. 171.—Brush Rigging of 500-Kilowatt Westinghouse Turbo-Dynamo.

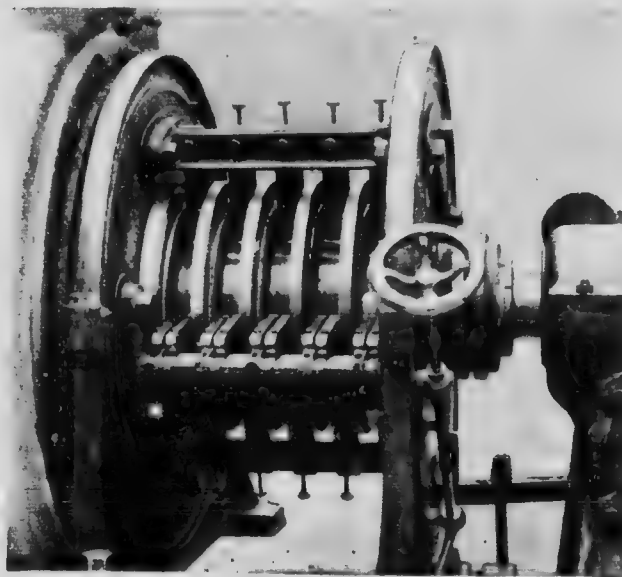


Fig. 172.—Commutator and Brush Rigging of 500-Kilowatt Westinghouse Turbo-Dynamo.

where it will be noticed that the dynamo, the brush gear and the pedestals carrying the bearings are each separately bolted to the foundations, a continuous bed-plate not being used.

Mechanical Balancing.—The fact that, for all intents and purposes, the rotating part of a dynamo or motor is dynamically similar to a spinning-top, must not be lost

sight of, nor the laws of simple rotational mechanics ignored. A few experiments with spinning-tops under different conditions would not be uninteresting, but space forbids us to describe them in detail. It is, however, a matter of common knowledge that if a top be out of balance it does not spin quietly, but wobbles; or, to put it otherwise, if the usual axis were prolonged and placed in bearings and the unbalanced top spun, the bearings would be strained, and if the caps were removed the rotating top would jump out of them. The same kind of thing will happen with an unbalanced rotating armature or field magnet,

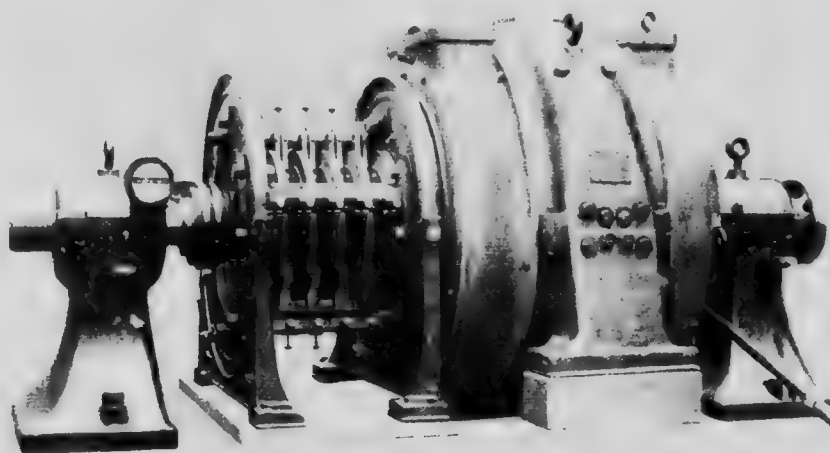


Fig. 173.—Showing Mounting of Westinghouse Brush Gear and Dynamo.

and if the error in balance be very great, serious disaster may occur, especially at high speeds.

The principal dynamical law with which we have to deal is easily understood. If a single small mass m be rotating in a circle of radius r round a centre c with uniform angular velocity, ω , the motion will give rise to a centrifugal force on the mass directed outwards from the centre, which must be counteracted (say, by the pull of the string to one end of which the mass m may be attached) if the body is to be kept in the circular path. Now we know from mechanics that this

$$\text{Centrifugal force} = m r \omega^2.$$

If, therefore, we have several small masses rigidly connected together and revolving with uniform angular velocity round a common axis, each of them will give rise to a force along a line drawn from its centre of motion through

its own small mass, and of a magnitude which can be calculated by the above formula. If these forces are not in equilibrium there will be a tendency, measured by the magnitude of the resultant force or couple, to displace the axis, and any fixed bearings which resist this tendency will be strained.

If these forces were all in one plane the conditions for equilibrium would be simple, for they would then all pass through the same point—namely, where the axis cuts the plane. In that case these conditions would be mathematically the same as the conditions which would have to be fulfilled if the weights of the masses m were to be balanced round the axis. Even if the centrifugal forces are not all in one plane these conditions are still amongst those which must be fulfilled, though they are no longer the only ones.

Hence one method of testing the balance of a finished armature is to place it with two points as near as possible to the opposite ends of the axle, resting on carefully levelled knife edges, as shown in Fig. 174. The armature should then be slowly rotated, and the tendency to roll along the knife edges observed in a sufficient number of

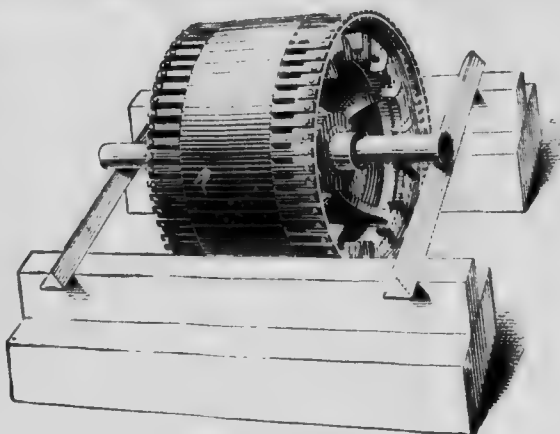


Fig. 174.—Testing the "Balance" of a Rotor.

positions. If in every position there is no tendency to roll, the above-named conditions have been fulfilled, and so far the armature is satisfactorily balanced. If there is a tendency to roll in any position, it should be corrected very carefully.

This *static test*, as it is called, only shows that the gravitating masses of the armature are in equilibrium as a whole, whereas the rotational conditions of balance require that the gravitating masses in every plane at right angles to the axis shall be in equilibrium, so that in no one of these planes shall there be any resultant centrifugal force. Such forces, if existing, might not balance one another, although the static test had been perfectly satisfied. If not in balance they would at each instant give rise to a resultant couple tending to twist the axis of rotation into a new position; in other words, there would be a greater or lesser tendency to wobble. Unfortunately, without spinning it there is no easily applied practical test which can be made on an armature which will satisfactorily determine

that in this respect it is in balance. All that can be done is to endeavour to build the armature as symmetrically as possible, and to apply carefully the static test above described.

Dynamos on Board Ship.—The fact that a dynamo armature is a swiftly rotating spinning-top should not be lost sight of in fixing the position of a dynamo on board a ship. The dynamical property to bear in mind is that when the axis of rotation is moved parallel to itself no additional forces act on the bearings because of the motion, whereas if the direc-

tion of the axis of rotation be forcibly changed, the bearings will be strained because of the resistance which the rotating armature offers to any change of this kind.

If, therefore, a high-speed dynamo be fixed with its axis fore and aft, no bad effect will be produced by the rolling of the ship, but, when the ship pitches, violent forces will be called

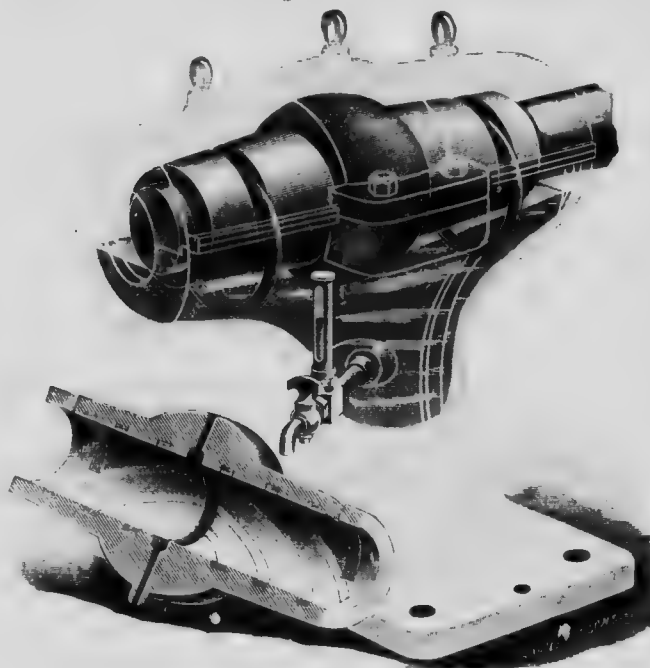


Fig. 175.—Self-Oiling Bearing used by the General Electric Company of New York.

into play which will tend to wrench the armature out of its bearings. On the other hand, with the axis of the dynamo fixed athwartships, the pitching will be harmless, but the rolling will be dangerous. In ships which roll heavily the dynamo should therefore be fixed with its axis fore and aft, whilst in those which pitch the dynamo should have its axis athwartship. Since all ships both roll and pitch more or less according to the state of the sea and other factors, it would be dynamically advisable to place the dynamo and its driving engine in a cradle mounted on gimbals. The action of the gimbals would be assisted by the dynamical reaction of the armature, but the device is not at present within the range of practical engineering politics.

Lubrication.—Where machines have to run weeks or even months and years without stopping, the problem of designing an efficient system of lubrication for all rubbing surfaces is one which merits very serious consideration. Apart from the worry, annoyance, and loss caused by a heated bearing, which may throw a whole station out of gear if it occurs at a critical time and in a critical position, the mere cost of lubricants is by no means a negligible item in a large generating station, and this cost may be appreciably reduced by care and foresight. This is not the place to discuss the theory of lubrication or to classify the almost innumerable methods which have been devised from time to time. A few words, however, may be devoted to methods which have been successfully used in large generating stations and sub-stations.

The reader is probably familiar with ordinary lubricators using various lubricants, and with the more modern sight-feed and other kinds of lubricators. Most of these are unsuitable for machinery which may have to run for long periods without attention, and some form of self-oiling bearing, which may be trusted to run for one or more months without the lubricant being renewed, is almost indispensable. A bearing of this kind, which has been widely used in different forms for electrical machinery, is shown in Fig. 175. The pattern here illustrated is used by the General Electric Company of New York on the large Edison dynamos. In the figure the pedestal is represented as if it were partly transparent, so as to exhibit the method by which the oil is kept in circulation. The stock of oil is kept in a hollow space in the pedestal below the shaft, whence it can be drawn off by the tap, its level being indicated in the gauge glass. One of the vertical halves of the bushing is shown dismounted at the side. When in place the bush has two slots on its upper surface, one near each end; in each of these is placed a large ring, which hangs upon the revolving shaft and rotates slowly when the shaft is running. The lower parts of the rings dip into the oil of the reservoir, and as the rings revolve oil sticking to them is carried up and delivered more or less on to the shaft at the slots. It is then worked along the spiral grooves in the bush towards the central outlet, by which it is returned to the reservoir. The same oil is therefore used over and over again, and need only be removed when it becomes too dirty for further use, and even then it may be filtered or otherwise purified and used once



Fig. 176. —British Thomson-Houston Self-Oiling Bearing.

more. With good oil renewal is not wanted oftener than once in three or four months.

Another and very similar form of self-oiling bearing used by the British Thomson-Houston Electric Company in their moderate-speed motors is shown in Fig. 176, in which the method used can be made out without further description. Both in this and in the preceding bearing the spherical seating of the central portion of the lining gives a certain freedom for self-adjustment and alignment, which is often very useful.

In a fair number of the illustrations given elsewhere details of self-lubricating bearings appear—for instance, in Plate III. and in many of the smaller figures.

In some of the largest stations, especially those utilising water-power, a system of forced lubrication is often adopted. In such systems the oil or lubricant is supplied to the bearings under pressures, and is literally forced through them by a pump. Here, again, the same lubricant may be used over and over again.

VIII.—REGULATION

In the early days of the development of the supply of electric power from central generating stations, the problem of regulating either the voltage or the current supplied attracted a great deal of attention, and gave rise to many ingenious inventions. At the present time this problem is not less but rather more important than it was then, and it is therefore proposed to devote a little space to examining the solutions which are recognised as good and successful in modern practice.

The two chief cases which arise are (1) the supply of electric power at a *constant voltage*, the amount of power dealt with rising and falling with the current, and (2) the supply of power by means of a *constant current*, the variation of the amount of power supplied being obtained by raising and lowering the voltage. In the first case, the voltage may have to be kept constant either at the dynamo or station terminals, or the conditions may be such that it is desirable, if not essential, that the voltage should be kept constant at some distant point.

It is obvious that the most convenient solutions will be such as act quite automatically and without the intervention of any attendant, or that in both cases cited the generators themselves should be so constructed that they will furnish either the pre-arranged voltage or the pre-arranged current, whatever the output required may be in kilowatts. Nevertheless, especially in the first case, the sole or partial use of hand control is so simple that it is often widely used. We propose to deal with the two chief cases separately in the order given.

Regulation for Constant Voltage or P. D.—The two chief methods of maintaining the P. D. constant at the terminals of the dynamo, or even

at some distant point, whatever may be the fluctuations in the output of the machine, are :—

(a) Compound winding ;

(b) A resistance, variable by hand, in the shunt circuit.

Unless otherwise stated, it will always be assumed in what follows that the speed at which the machine runs is kept absolutely constant at all loads.

(a). *Compound Winding*.—Considered as a method of excitation this has already (see page 6) been explained and diagrams given (Figs. 1 and 2), showing how the circuits are arranged in different cases. A shunt-wound or a separately excited machine is necessarily taken as the starting point, for it is only such a machine that will give full pressure on its terminals at no load. In a series machine the pressure on the terminals at no load is practically *nil*. On the "external characteristics" given in Fig. 490, Vol. I., *O A* is the starting pressure of both the shunt-wound and the separately excited machines, whilst the initial pressure of the series dynamo is represented by the negligible quantity *o s*.

In both the curves which start from *A*, however, the pressure is not maintained as the external current or load increases, but falls off, at first slowly and afterwards more rapidly. It has been explained that this is due to :—

(a) The increase in the "lost volts" due to the larger and larger currents that are being forced through the armature.

(b) The increasing effect of the armature reactions as the current through it increases.

To neutralise both these causes of loss of pressure at the terminals, increased field-magnet excitation is necessary, so that (i.) the total flux shall be increased as the load increases, and an additional E.M.F. generated equal in amount to the "lost volts," and (ii.) additional ampere-turns shall be supplied to the magnetic circuit to balance the demagnetising ampere-turns of the armature, which increase proportionally with the increase in the armature current as the load increases. The desired result can be attained more or less perfectly by winding round some convenient part of the magnetic circuit—usually in the neighbourhood of the shunt exciting coils—a sufficient number of turns, connected as shown in Fig. 1 or 2, through which practically the whole armature current passes. The ampere-turns thus added to the excitation of the machine will rise and fall with the load, and it is therefore important to be able to calculate exactly how many extra turns will be required in order to produce the desired effect on the pressure at the terminals.

Calculations.—The volts lost at various loads because of the internal resistances of and currents in the machine are readily calculated when the data are given.

Thus, for a certain 15.5-kilowatt bipolar dynamo which gives 70 amperes at 220 volts, the resistances are :—

Armature resistance = 0.132 ohm.

Series coils do. = 0.043 ohm.

Shunt coils do. = 116 ohms.

The shunt current is therefore 1.4 amperes $\left(\frac{220}{116}\right)$, and for the "long shunt" connection (Fig. 2) the

Lost volts = $71.4 \times 0.175 = 12.5$ volts.

For the Salford 10-pole dynamo (see Fig. 16, page 16), the data were :—

Armature resistance = 0.00425 ohm.

Series coils do. = 0.0028 ohm.

Shunt coils do. = 30 ohms.

The full load was 1,600 amperes at 500 volts, and therefore the shunt current was 17 amperes and the total armature current 1,617 amperes. Again, assuming long shunt connections, the

Lost volts = $1,617 \times 0.00705 = 11.4$ volts.

The necessary modifications for "short shunt" connections (Fig. 1) are obvious.

To both the above calculations it may be objected that the value of the resistances of the series coils has been taken into account, and that before settling the number of turns you cannot know this resistance. It is, however, quite allowable to assume a probable value, which should always be much less than the known armature resistance, for the required number of turns can be obtained with any reasonable resistance by properly choosing the cross-section of the conductor.

The lost volts having been ascertained for various loads, the increased flux required to produce the necessary extra E. M. F. can be calculated from the fundamental formula (see page 513, Vol. 1):—

$$E = \frac{n Z N}{10^8},$$

and the next problem is to calculate the additional excitation which will provide this flux. Mere proportional increase of the ampere-turns will not be sufficient, for the permeability of the iron part of the circuit diminishes as the flux increases. Recourse must therefore be had to the method already described (see page 45) for calculating the initial ampere-turns, and it is convenient to embody the results in a curve connecting load and excitation.

There still remains to be calculated the additional excitation required on account of the armature reactions. When the method of winding the armature is known, it is comparatively an easy matter to determine the number of turns through which the demagnetising portion of the armature current flows, and at first sight it might be supposed that the simple

addition of an equal number of magnetising turns on the field-magnet core would suffice to restore the cancelled excitation. This, however, is not the case, for it must not be forgotten that, because of magnetic leakage, all the lines passing through the core of the magnetising coils do not pass through the armature. Moreover, because of the increased excitation required to compensate for the "lost volts," the "leakage factor" (see page 47) is not the same at different loads, and the effect of the cross-magnetising field should not be overlooked (see note, page 47), and finally the diminished permeability of the magnet cores due to the increased flux should be taken into account. By keeping these points in view it will not be difficult to add to the curve previously drawn the additional excitation required at various loads to compensate for the demagnetising effect of the armature currents.

Should the final curve be a straight line, it will be easy by division to find the number of turns which, when wound on the magnet cores and fed with the load current, will give the required additional excitation. As a rule, the curve will not be straight, and a mean value must be adopted for the number of turns required. It is frequently the custom to choose such a value that the volts required are obtained at no and full loads, whilst at intermediate loads a small rise of voltage is allowed.

The difficulty of getting exact regulation at all loads by compound winding is due to the increasing flatness of the magnetisation curve as the flux density increases. The consequence is that the ampere-turns near full load are not so effective as the ampere-turns at light loads. To meet this difficulty an ingenious device, which they call a *compounding rectifier*, has been used by the Crocker-Wheeler Electric Company. It consists in placing in parallel with the *series* coils a resistance so constructed that it becomes considerably heated at full or near full load. In consequence of this heating the resistance of this parallel circuit rises, and a greater proportion of the current goes through the series coil, thus increasing the ampere-turns more rapidly than the current, and giving a flatter characteristic to the compounded machine.

As an example of the calculation of the ampere-turns necessary for compounding, reference may be made to the machine for which the details of the calculation of the "no-load excitation" for a particular point are given at page 48. The point to which those details relate is, as explained, the point corresponding to an E.M.F. of 115 volts, and the ampere-turns obtained are 16,607. For the normal voltage of 105 volts the magnetisation curve shows an excitation of 10,950 ampere-turns, and it is for this normal voltage that compounding is required. Calculations similar to those given on page 178 show that the "lost volts" at full load are 6.6 volts, and therefore for full load an E.M.F. of 111.6 ($105 + 6.6$) volts will be required, and the magnetisation curve shows that for this voltage 13,430 ampere-

turns are required, which means an addition of 2,380 ampere-turns. But at full load a lead of 22.5° has to be given to the brushes, which produces a demagnetising belt 45° wide, containing 15 armature-turns, which at full load (100 amperes) means that the demagnetising ampere-turns of the armature are 1,500. As the leakage factor is 1.28, the compensating ampere-turns wound upon the magnet cores must be

$$1,500 \times 1.28 = 1,920.$$

Thus we obtain finally:—

Compensating ampere-turns for "lost volts" = 2,380

Compensating ampere-turns for "armature reaction" = 1,920

Total "series" ampere-turns required 4,400

an increase of 40 per cent. on the no-load ampere-turns (10,950) supplied by the "shunt" circuit. The actual compensating ampere-turns found to be necessary by experiment were 4,600.

As another example the following calculations were given by Mr. Parshall, in the *Street Railway Journal* of New York. They refer to a 10-pole dynamo designed to give, at 90 R. P. M., an output of 550 kilowatts, or 1,000 amperes at 550 volts. From the data there given, the following table has been compiled for the part of the whole magnetic circuit served by one pole:—

MAGNETIC CALCULATIONS FOR A 10-POLE DYNAMO

Parts of Magnetic Circuit.	B (gausses).		A		Ampere-turns.	
	No load.	Full load.	No load.	Full load.	No load.	Full load.
1. Armature. (a) Core ...	9,150	10,400	.000115	.000171	190	320
— (b) Teeth...	16,750	18,500	.000206	.000480	340	900
2. Gap	6,600	7,530	.003030	.003041	5,000	5,700
3. Magnetic core	12,100	13,030	.000474	.000816	880	1,530
4. Yoke	10,700	12,250	.000345	.000534	640	1,000
			.004170	.005042	7,050	9,450
Percentage increase, no load to full load ...			21		34	

In addition to the 9,450 ampere-turns required to give the necessary flux through the increased reluctance at full load, 2,900 ampere-turns were required to counteract the demagnetising effect of the armature current.

For the purposes of the designer, it is necessary to calculate the ampere-turns of excitation required at different loads, but from the point of view of the user the more interesting information is the actual power spent on excitation under various conditions. The following figures for the Mather and Platt 10-pole dynamo previously referred to are therefore instructive, as showing the performance in this respect of a well-designed machine.

Power required for excitation at no load = $3\frac{1}{2}$ kilowatts.

Power required for excitation at half load = 4 kilowatts.

Power required for excitation at full load = $5\frac{1}{2}$ kilowatts.

The increase in the power required for excitation is therefore 23 per cent. at half load and 61 per cent. at full load. The still more interesting point is that at the full load of 800 kilowatts the power used for excitation is only 0.66 per cent. of the output.

As another example, we may take the 15.5-kilowatt dynamo referred to at page 178. This machine has 8,900 turns in its shunt circuit and 88 turns in its series circuit, whence we find

Ampere-turns of shunt circuit = 11,000

Ampere-turns of series circuit at full load = 6,300

17,300

the increase between no load and full load being 57 per cent. In regard to the power used for excitation the figures already given show:—

Power required for excitation at no load = 308 watts.

Power required for excitation at half load = 365 watts.

Power required for excitation at full load = 527 watts.

There is, therefore, an increase of over 70 per cent. in the power used for excitation between no load and full load, whilst at full load the power spent in excitation is 3.4 per cent. of the useful output; but it should be noted that the machine is quite a small one. From the point of view of size, the comparison of the figures for the two machines dealt with is instructive.

In regard to the placing of the series coils relatively to the shunt coils, different designers in turn make use of almost every available position, and some of these have already been illustrated. Thus, in Figs. 15, 21 and 22 the compounding or series coils are shown as placed behind the shunt coils, whilst in Fig. 25 they are wound over or outside the shunt coils. In Plate II. and Fig. 11, on the other hand, the former position is reversed, and the "main" or series coils are placed nearer to the pole faces than the shunt coils. From this diversity of practice it may be inferred that there are no very strong reasons for choosing one position rather than another, and such is, indeed, the case. The placing of the coils alongside one another facilitates repairs in the event of a breakdown of insulation, but would appear to necessitate the lengthening of the core. This is not, however, so, since with a given depth of winding the length of coil is, as we have seen, fixed by the ampere-turns required and the temperature rise. When the coils are wound over one another, it would appear desirable to place the series coils outside, for the inner turns of an ordinary magnetising coil are, for a given amount

of excitation, cheaper than the outer turns. As, therefore, the maximum excitation is only required from the series coil at full load, and as at lower loads the turns are not carrying full current, it would appear more reasonable to give them the less advantageous position, and to place them, as



Fig. 177.—Regulation by Resistance in Shunt Circuit

in Fig. 25, outside the shunt coils.

(b). *Resistance in Shunt Circuit.* — An economical and very often not inconvenient method of controlling the P. D. of a shunt-wound dynamo, which

has been and is still widely used, is to introduce a variable resistance into the exciting circuit. The added resistance certainly wastes some energy, but the waste need only amount to a small percentage of the total output. For the lower limit of the voltage or for no load the whole of the resistance is in circuit, the arrangement being as shown diagrammatically in Fig. 177, but with the movable arm *a* on stud 1. As the load increases, the tendency of the P. D. at the terminals to fall can be counteracted by moving the arm *a* successively on to the studs, 2, 3, 4, 5, etc., thus reducing the resistance in the exciting circuit and increasing the exciting current (if only the P. D. does not fall) and the excitation as expressed in ampere-turns. The resistance must be so constructed that it will carry the full exciting current without over-heating. A form very widely used for general experimental work is shown in Fig. 178,* but for placing behind switchboards and in special positions other patterns are used, some of which will be referred to later.

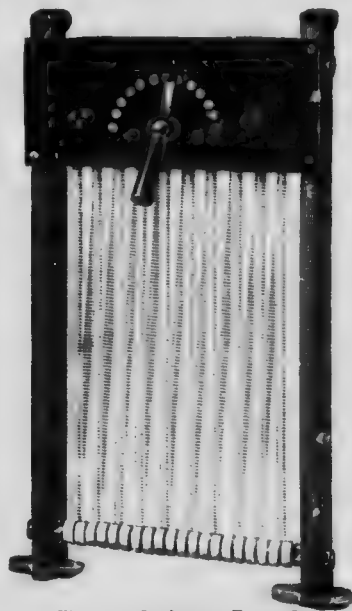


Fig. 178.—Resistance Frame for Shunt Regulation.

One of the defects of this method of control is that, unless the contacts are numerous, so that the mean resistance between the contacts is relatively small, the change made by passing from one contact to another has sometimes too great an effect upon the voltage. On the other hand, for numerous

* Lent by Messrs. Nalder Bros. & Thompson.

contacts the arrangement becomes somewhat costly, and the necessity of properly insulating the separate coils may make it unwieldy and cumbersome, though this objection is ingeniously overcome in several modern designs of field-control rheostats.

In the design of such rheostats it must not be overlooked that although the main object of the rheostat is to reduce the voltage at the terminals of the field coils of the generator so that these coils shall only give the excitation necessary at the moment, the method by which it accomplishes this object is by converting into heat that portion of the energy of the exciting current which is due to the excess voltage. In other words, although the real object is to cut down the voltage, the method adopted is to waste energy. It is this energy deliberately wasted which it is the function of the rheostat to dissipate harmlessly in the form of heat. This it must do without danger to surrounding plant and apparatus, and without being itself racked and destroyed by necessarily repeated heatings and coolings. These conditions apply to all control rheostats for power circuits. We are concerned at the moment only with the solutions adopted for the field control of generators.

For this purpose, as the most convenient position for the rheostat is on the

switchboard, where either in front or at the back space is valuable, designers have aimed at fulfilling the conditions in the smallest possible space, and with this object the necessary conductors are very often embodied in a fire-proof insulating cement, which is as good a conductor of heat as can be found fulfilling the usually antagonistic condition of being a good electrical insulator.

A good idea of the general trend of the design of the apparatus available can be obtained by considering the field rheostats of the British Thomson-Houston Company. Three types are available, differentiated by the quantity of energy to be dissipated. For small amounts there is the "plate" type, for larger the "tube" type, and for the largest currents required in modern practice the "grid" type. An example of the "plate" type is shown in Fig. 179, in which six of the largest size of plates, with their contacts complete, are mounted in a frame and placed electrically in

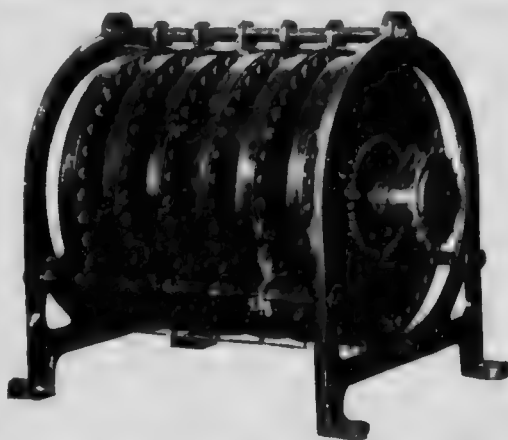


Fig. 179.—British Thomson-Houston "Plate" Type of Field Rheostat.

parallel. This represents the largest standard size of this particular type. Each plate, which is 15 inches in diameter, appears on inspection to be filled with cement; in this cement, however, the resistance coils are embedded, forming electrically one continuous conductor to which electrical access can be obtained at regular intervals through two rings of contact studs

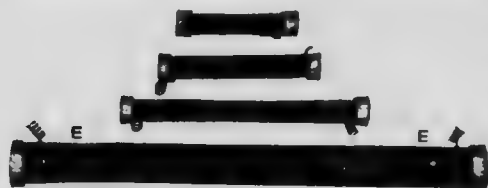


Fig. 180.—British Thomson-Houston "Tube" Resistances for Rheostats.

which can be clearly seen on the front of the right-hand plate in the figure. The conductor used is a special alloy with a low temperature coefficient. The hubs carrying the contact arms are all mounted on the same spindle, and can be turned into any

position by rotating the sprocket wheel shown in the figure or by rotating a hand wheel which is substituted for it for manual operation. The electrical circuit connections are those of Fig. 177, but the contacts are much more numerous.

In the second or "tube" type of rheostat the resistance wire is wound upon a cylindrical fireproof tube, and then coated with an insulating and protecting compound. Several sizes of these tubes as they appear when completed, and with the ends of the resistance wires brought out, are shown in Fig. 180. The ends of the tubes are bushed with porcelain. These tubes can be mounted directly on the switchboard panel, though this is not recommended. The more usual plan is to mount them on one side of a slate base, on the other side of which the contacts

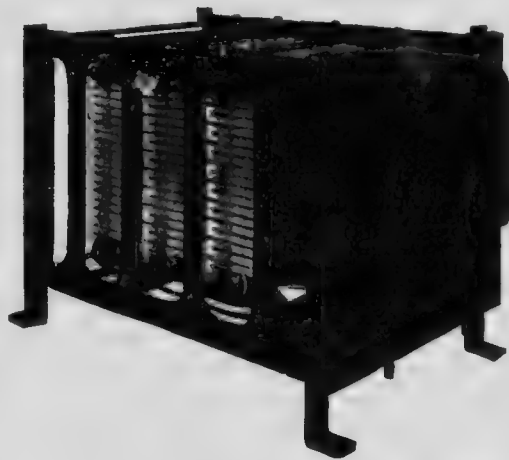


Fig. 181.—British Thomson-Houston "Grid" Type of Rheostat for Heavy Currents.

for a radial contact arm are arranged to be operated in much the same manner as for a single "plate" rheostat. Tubes of the E E size of Fig. 180 are made up to a standard maximum rating of 50 amperes. The lighter tubes are for smaller currents.

For the heaviest currents the "grid" type of rheostat shown in Fig. 181 is used. In this type the resistance material is in the form of grids whose

shape can be readily made out in the figure. These grids are assembled in a supporting framework from which they are insulated by mica. One end of the frame carries a slate slab, upon which are mounted contacts substantial enough for the heavy currents to be handled. The slab also carries, with a supporting bracket, an axle upon which are mounted the usual radial contact arms, which at their ends carry copper plunger brushes, in which the copper brushes are pressed firmly against the contact studs by suitable springs. It is claimed that this construction secures maximum conductivity with minimum friction. The rheostats are made in standard sizes for carrying currents up to 150 amperes.

In regard to the number of contacts available at a point referred to on page 182, the "plate" type is made in three sizes, with 35, 50, and 70 resistance divisions respectively. The "tube" type is similarly supplied with numerous contacts, and the standard grid types divide the available resistance into from 70 divisions for the lighter currents down to 40 divisions for the heaviest currents. Some examples will be referred to presently.

All the rheostats can be operated by hand wheels mounted on their axles or by chains passing over sprocket wheels similarly mounted, as shown in Figs. 179 and 181, and driven from some convenient position at the switchboard. One method of operating in this way is shown diagrammatically in Fig. 182, in which a hand-wheel *H* is mounted on a vertical shaft carried by a pedestal on the switchboard platform. This shaft works the spur gear *G* below the platform, rotating the horizontal shaft *S*, from which the sprocket wheel of the rheostat can be driven, the rheostat itself being placed in any convenient position, such as *R*₁ or *R*₂, where space is not so valuable as it is closer to the switchboard.

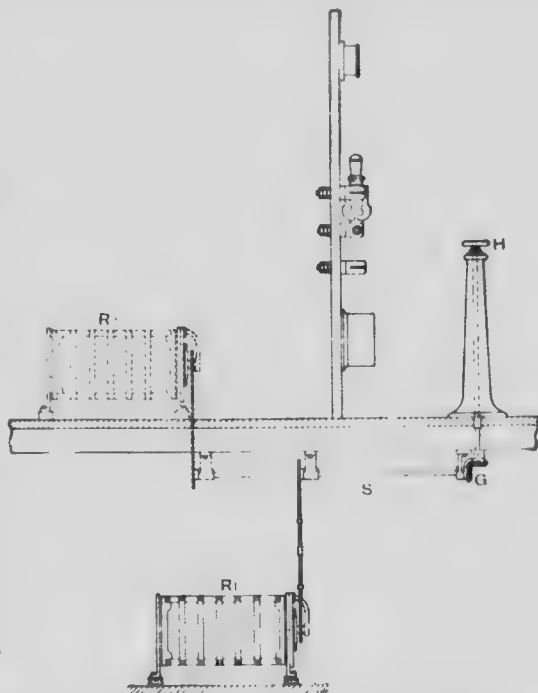


Fig. 182. Mechanical Operation of Field Rheostats.

Automatic Control of Field.—It is further obviously possible to drive these axles electrically, and this possibility opens up the additional possibility of the control being made automatic so as to be operated whenever the circumstances so require, thus approximating to the automatic control furnished by "compounding."

As examples of such control, particulars are given of one of two different kinds of apparatus, one ratchet-driven and the other motor-driven, as designed by the British-Thomson-Houston Company. The front of the rheostat arranged for the axle to be ratchet-driven, is shown in Fig. 183, in which the sprocket wheel of preceding figures is replaced

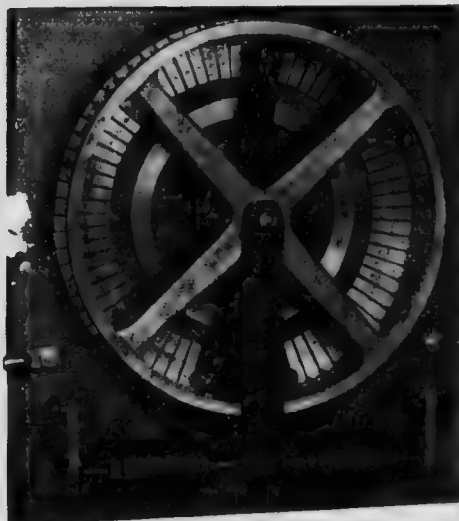


Fig. 183.—Electrically Controlled Field Rheostat (Ratchet Driven).

by a large four-spoke wheel of the full diameter of the contacts, and carrying on its inner periphery the necessary teeth for engaging with the pawl, which can be partly seen at the bottom behind the supporting bracket. There are two such pawls, one to be operated by the left-hand solenoid for rotating the wheel clockwise and increasing the resistance in circuit, and the other to be operated by the right-hand solenoid to rotate the wheel in the opposite direction. A diagram of the connections is given in Fig. 184, in which for clearness the rotating parts, the pawls, and some of the contact sectors are omitted.

The rheostat is placed between one of the busbars and the motor field F by its main contacts T_1 and T_2 , one of which, T_2 , is joined directly to the first contact "1" and the other T_1 to the revolving contact arm (not shown) through the continuous ring $N N N$. The control is effected through a single-pole throw-over switch $B A C$, which is mounted on the switchboard. When this switch is thrown over to the left so as to join the contacts A and B the left-hand solenoid L is energised and the pawl moves the wheel one notch: At the limit of its travel its core a_1 opens the contact D_1 , breaking the solenoid circuit and allowing a strong spring to pull the pawl and armature back to the neutral position. This, however, again closes the contact D_1 and the operation is repeated as long as the switch $A B$ remains closed. If the switch is thrown over so as to close the contacts $A C$ the right-hand magnet R is energised

and the wheel is rotated counter-clockwise. To prevent the wheel being rotated too far in either direction the limit switches E_1 and E_2 are arranged to be struck and opened by the rotating arm when it reaches the last stud on either side; E_1 , whilst held open, breaks the circuit of L , and E_2 breaks that of R .

It could be arranged for the switch, BAC to be worked automatically as the voltage of the generator rises and falls; but under present

conditions it is considered unnecessary to complicate the circuits by making such an arrangement; the switchboard attendant has simply to hold the switch over until his voltmeter shows that the right voltage

has been attained, and then open it by hand. If necessary, a spring can be arranged to ensure that it is not carelessly left permanently closed.

In the regulator designed by Messrs. Brown, Boveri and Co., Limited, a small series-wound motor is used to vary the resistance in the shunt-circuit of the dynamo.

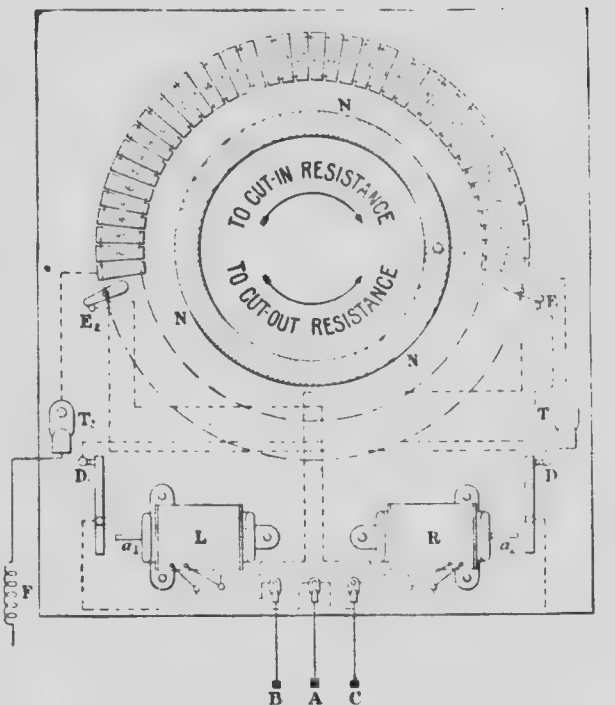


Fig. 184.—Connections of Electrically Controlled Field Rheostat.

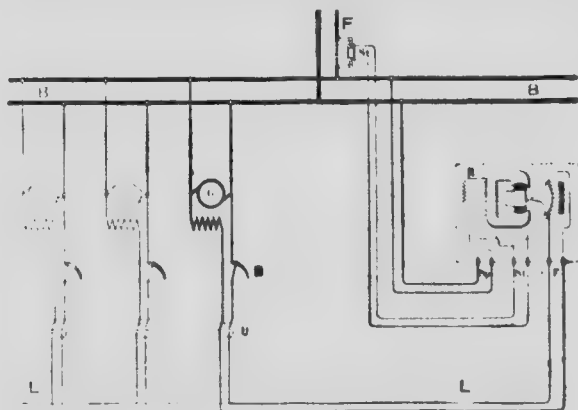


Fig. 185.—Brown, Boveri & Co.'s Regulator used with Self-Exciting Generators.

The movement of the armature is controlled by spiral springs, so that it can only rotate through a small range of arc within which it effects the necessary changes in the resistance.

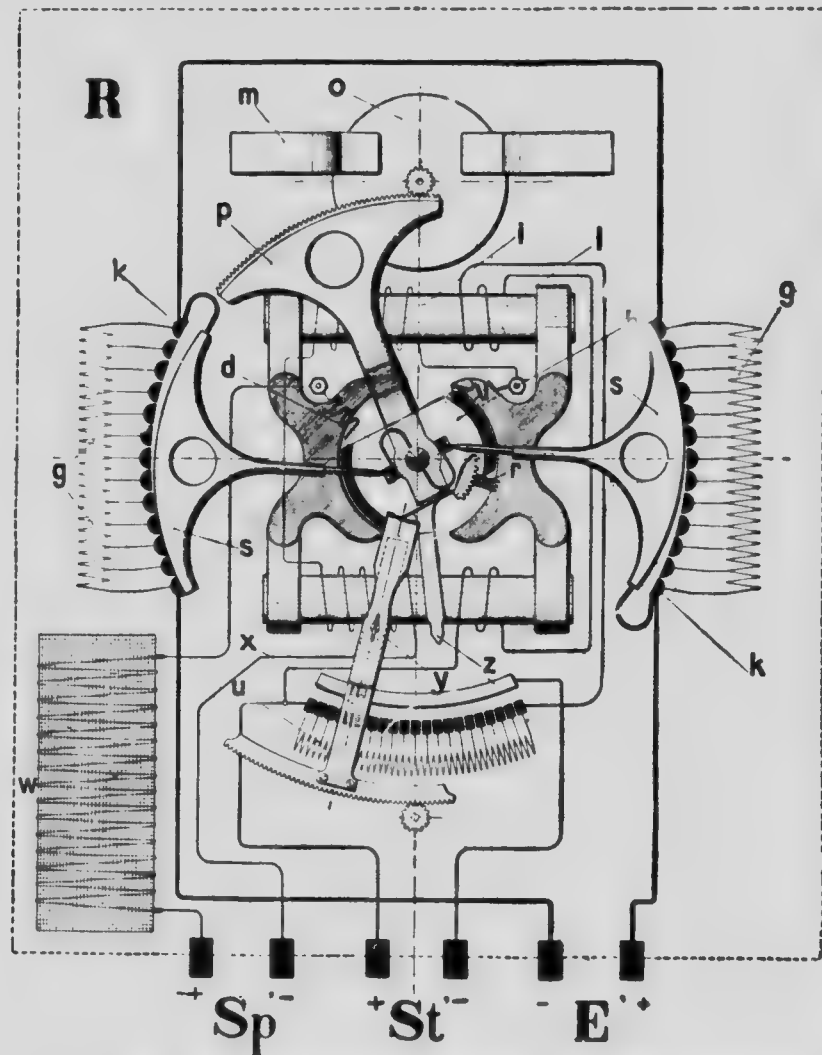


Fig. 185.—Diagram showing Internal Connections of Brown, Boveri & Co.'s Regulator (Motor Driven).

The general plan of the connections for controlling three dynamos working in parallel on the same busbars is shown in Fig. 185, whilst the circuits and further mechanical details of the regulating motor are depicted

Diagrammatically in Fig. 186. The regulator has three pairs of terminals. The first pair *E* is connected to special regulating leads *L L*, which can either be thrown into or cut out from the shunt circuits of the dynamos by the switches *U*; these circuits can further be adjusted independently of the regulator by the variable resistances indicated at *M*. The second pair of terminals, "*St*" is connected to the two ends of a low resistance inserted in one of the leads carrying the load current, and, therefore, has always a P. D. which rises and falls with the load current. The third pair of terminals "*Sp*," is joined directly to the busbars *B B*, and its P. D. will rise and fall with the voltage of these bars.

Turning now to the diagram of the regulator itself, Fig. 186, it will be seen that the terminals *E* are for the purpose of throwing into the excitation circuit of any dynamo connected to *L L* so much of the resistances *g g*, as is not short-circuited by the moving sectors *s s*, whose position is controlled by the position of the motor armature *h*. If the circuit connected to the terminals "*Sp*"

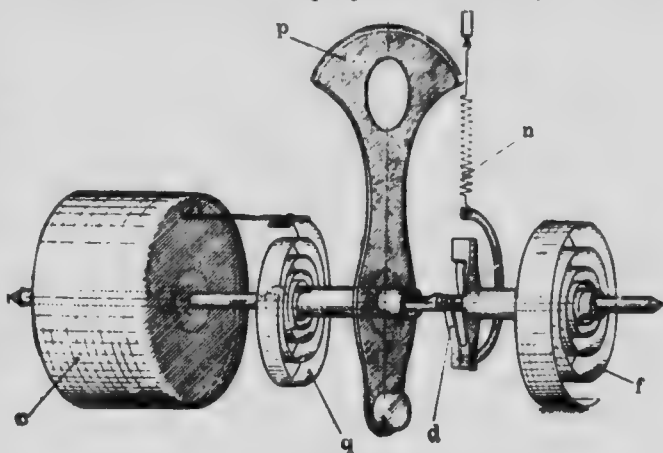


Fig. 187. — Fittings and Shaft of Regulating Motor.

be next traced out, it will be found that it consists of the resistance *w* in series with the armature *h* and the main excitation coils, *i*, of the field magnets of the regulating motor. The motor is therefore primarily a series motor placed direct on the busbars, the resistance *w* being introduced merely to reduce the current used. The torque of the armature being proportional to the current in the armature and the field flux, will, therefore, initially depend on the voltage of the busbars, and if the terminals "*St*" are not in circuit the position of the armature will be determined by this voltage and the controlling torque. This controlling torque is supplied by two spiral springs, *f* and *q*, whose positions are shown in Fig. 187, which depicts the shaft of the motor stripped of its electrical windings, and in which *h* again represents the body of the armature. The shaft also has attached to it flexible springs *d* (Figs. 186 and 187), which carry jewelled bearings, which press against the pivots of the radial shafts,

carrying the sectors *s*. The springs, therefore, hold the sectors against the contacts *k k* (Fig. 186), along which the sectors roll with a minimum of friction, short-circuiting a definite number of coils for each position of the armature. In this way the resistance in the shunt circuit of the dynamo is increased if the busbar voltage rises, and diminished if it falls, the normal voltage in which everything is in equilibrium being adjusted by the screw *r* (Fig. 186), which regulates the torque produced by the spiral spring *f* (Fig. 187).

The damping is magnetic, and is effected by the rack on the sector *p* rotating the aluminium disc *o* between the poles of the magnets *m*. This method of damping has been fully explained elsewhere (see page 722, Vol. I.).

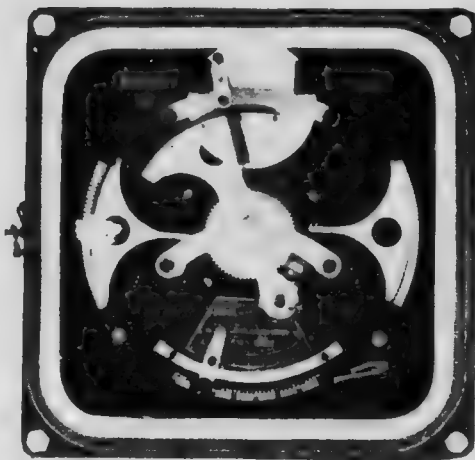


Fig. 188. - Brown Boveri & Co.'s Field Resistance Regulator.

resistance, and to increase the busbar voltage. It may thus be arranged that for periods of heavy load in a tramcar system, the busbar voltage may be increased to any predetermined value above the normal, say from 500 to 550 volts, an increase of 10 per cent.

The actual regulator ready for mounting on a panel is shown in Fig. 188, which should be carefully compared as to details with the preceding figures. It is claimed that the action of these regulators is very rapid, and that they are so sensitive that the pressure can be maintained constant within one per cent. Their use for alternating current generators and in other directions will be referred to later.

In conclusion, other firms have dealt successfully with the various problems of rheostatic control of generators; but as these problems come up again in a more complicated form in connection with the control of

The circuit between the terminals "St" is used for *over-compounding*. It consists of a field winding *l* in parallel with more or fewer of the resistances *u* (Fig. 186). The field winding is connected up differentially so as to oppose the main excitation of the motor. As therefore the load on the feeder *F* (Fig. 185) increases, the current in this circuit weakens the field more and more, thus producing the same effect as a fall in the voltage of the busbars. The armature of the motor, therefore, moves so as to cut out some of the dynamo shunt re-

alternators and of continuous current motors, further illustrations are postponed until these subjects are taken up.

(c) *Third-Brush Regulation.*—In some of the machines of Messrs. Mavor and Coulson an ingenious method of regulation proposed by Sayers was used for a time. This consisted in drawing the excitation current from a third brush so placed on the commutator that the distortion of the field as the load increased raised the voltage on the excitation circuit sufficiently for regulation purposes. The method kept the P. D. constant and dispensed with the control rheostat, therefore saving the energy wasted therein. It is fully described, with a diagram of results, in the last edition of this book, but as it is not now used it is considered unnecessary here to do more than refer interested readers to that description:

(d) *Electric Governing of Engine.*—When the prime mover used to drive the dynamo is a steam turbine the voltage can be kept constant by electrically controlling the speed of the engine, a method of regulation which, though not impossible, is not so readily applicable to reciprocating engines. The method was successfully developed by Messrs. C. A. Parsons and Co. in connection with their early forms of steam turbines. The governor of the engine consisted of a solenoid connected across the terminals of the dynamo, and acting upon a core controlled by a spiral spring. This core in moving up and down in the solenoid actuated a lever, which in its turn acted upon a small valve controlling a steam relay. In certain positions the relay admitted steam to work a piston which operated on the main throttle valve of the engine. At small loads the steam was admitted in equal puffs, and as the load rose these puffs became longer and longer, until at full load the admission of steam was continuous. The governor could be set to keep the voltage constant or to give any required range of voltage, and it was very prompt in its action.

Regulation for Variable (but nearly Constant) Voltage.—In many practical cases the machine is required to deliver energy in much the same way as a constant voltage machine—that is, the chief variation in the load is brought about by varying the current in the working circuit, but it is further desired to vary the voltage between the somewhat narrow limits of from 10 to 15 or 20 per cent. If the condition is that the volts are to rise to the above extent with the load, it can be met more or less satisfactorily by *over-compounding*. In this case the extra excitation required at the increased load is supplied by a series coil as in compound winding, but the number of compensating turns used is more than sufficient to keep the P. D. constant. Thus, with tramway generators the usual P. D. may be taken as 500 volts, but when the load is heavy this may require to be increased up to 550 volts, a rise of 10 per cent., to compensate for the voltage drop in the long feeders and distributors caused by the heavy currents. The rise at the generator is intended to keep the voltage more nearly constant

at the cars, and therefore the dynamos may be said to be compounded for a constant P. D. at some distant point.

Where the P. D. is required to be different at different times for the same load, it is obvious that the regulation cannot generally be automatic, and therefore the device already referred to of a variable resistance in the shunt circuit adjustable by hand is usually applied. Sometimes, however, the machine is compound wound, so that with the assistance of the series coils sufficient excitation will be obtained for the most severe conditions contemplated. The regulation is then made to consist in putting a variable resistance adjustable by hand in *parallel* with the *series coils* of the winding. This resistance drains off some of the current which would otherwise flow through the series coils, and therefore diminishes the ampere-turns of excitation available, until finally, when the series coils are short-circuited, they cease to have any effect on the excitation, and the machine becomes simply a shunt machine.

Charging Secondary Batteries.—A specially interesting case is that of the charging of secondary batteries. For reasons given elsewhere shunt machines should be employed for this work, and therefore compound winding cannot be relied upon to give the extra volts required as the charging proceeds. Moreover, the range required may be as much as an increase of 40 per cent. on the initial P. D. if no coils are cut out as the battery P. D. rises. The various methods of satisfying these and other conditions will be considered most conveniently in connection with the general subject of secondary batteries and their use in generating stations.

Regulation for Constant Current.—The problem of designing a dynamo so that under all loads, within proper limits, the current shall remain constant whilst the P. D. at the brushes varies with the load, is one which is not so readily solved as the corresponding one for keeping the P. D. constant. A glance at the external characteristics for series- and shunt-wound dynamos, given on Fig. 490, Vol. I., will show that no method of compound winding is available here. Some method of control external to the field magnets and armature is necessary, and such methods have been adopted for the high-pressure arc-light machines which have been most widely used.

The constant current regulators for the Brush arc light dynamos have been modified and improved from time to time, and some of the earlier forms will be found described in the previous editions of this book. A more recent form is shown diagrammatically with its connections to the machine in Fig. 189, where A and B are the positive and negative terminals of the dynamo, which will be found described on page 496, Vol. I., and *a* and *b* are binding screws connected to the ends of its field-magnet coils. The carbon resistance *c* is joined to *a* and *b*, and is therefore in parallel with these coils. By moving the lever *l*, the contact pressure, and with it the combined

resistance of the carbon blocks, can be altered, thus causing an alteration in the relative currents in the two circuits. The lever *l* is moved by the regulator magnet *M*, which is controlled by the relay magnet *R*. The external current of the machine passes through *R*, and when of the proper strength holds the armature *D* half way between the contacts *c* and *d*. The magnet *M* is wound with three sets of coils, *x*, *y*, and *z*, each of which is traversed by the main current in the normal state of

affairs shown in the diagram; of these, *y* and *z* each has the same number of turns, but *y* is connected up so that its magnetising action assists *x*, whilst the magnetising action of *z* is in the opposite direction. Thus, when *D* is in the central position, the main current traverses the three coils *x*, *y*, and *z*, but the magnetising effect is that of *x* only, since *y* and *z* mutually cancel one another. But if the main current becomes too strong, *D* is raised against the contact *d*, and the coil *z* is short-circuited and loses its current, leaving *x* and *y* both magnetising *M* in the same direction. Consequently the armature *F* is drawn upwards, the carbon blocks are compressed, more current flows through the carbon resistance, and less through the field-magnet coils of the dynamo. The dynamo E. M. F. therefore diminishes, and the main current falls off again to its normal amount. On the other hand, when the main current falls below its proper value, *D* drops on *c*, and the coils *x* and *y* are short-circuited, thus losing their current. Consequently the magnet *M* is now only energised by the difference in the ampere-turns of the coils

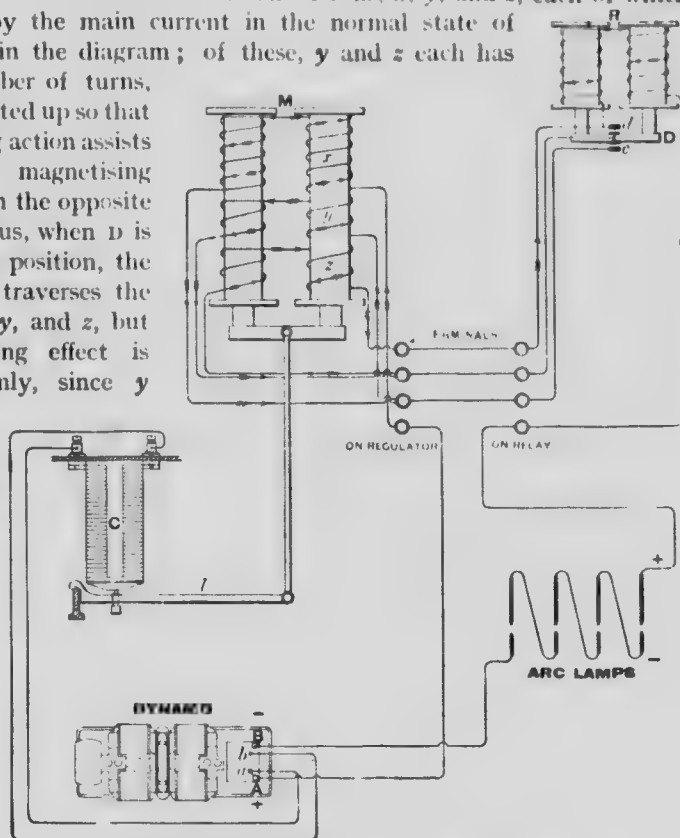


Fig. 189.—Brush Geipel Regulator for Constant Current.

magnetising *M* in the same direction. Consequently the armature *F* is drawn upwards, the carbon blocks are compressed, more current flows through the carbon resistance, and less through the field-magnet coils of the dynamo. The dynamo E. M. F. therefore diminishes, and the main current falls off again to its normal amount. On the other hand, when the main current falls below its proper value, *D* drops on *c*, and the coils *x* and *y* are short-circuited, thus losing their current. Consequently the magnet *M* is now only energised by the difference in the ampere-turns of the coils

x and z , and its armature F falls downwards and the pressure on the carbon blocks is diminished, their electrical resistance being therefore increased. Thus less current flows through c and more through the magnetising coils of the dynamo, whose E. M. F. therefore increases and restores the main current to its normal value.

The actual apparatus is shown in Fig. 190, the construction of which will be readily understood by a comparison with the diagrams in Fig. 189.

Other arc-light machines controlled by special apparatus to give a

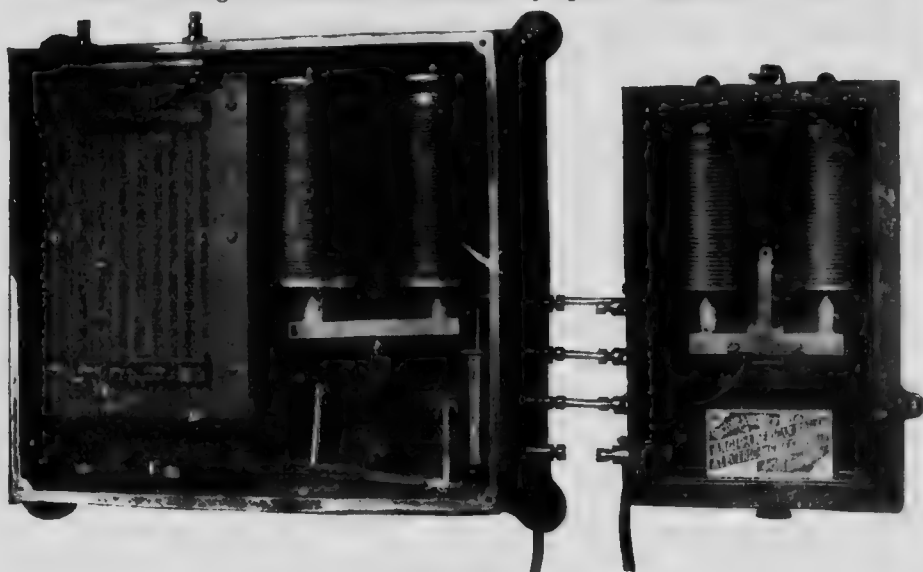


Fig. 190.—The Brush Regulator; Actual Apparatus.

constant current at a variable voltage were devised in the early days of arc lighting, but for all practical purposes these have now been superseded by the large central-station generators described elsewhere in this book. In other words, arc lighting has ceased to be dealt with by special generators, and when required is taken as part of the ordinary load of the generating station. The reader who is interested will find in the previous edition of this book (pages 824 *et seq.*) a full description of the regulating gear of the very ingenious and, at one time, widely used Thomson-Houston arc-light dynamo.

Thury's Method of Regulation.—In connection with his system of long-distance transmission by continuous currents of constant magnitude, M. R. Thury many years ago used regulators which either affect the magnetic field or the lead of the brushes. The chief feature of the system is the

connecting of several high-voltage continuous current dynamos, in series, thus raising the line voltage to a very high value, which in some cases has reached 30,000 volts, produced by eight machines in series.

Up to 8,000 volts the generators, with their armatures in series, were in the early days separately excited by a single exciter, which supplied currents in parallel to the field-magnet circuits. The exciter, in one typical instance, was driven by a turbine, which was controlled by a solenoid traversed by the main current of the generators. The solenoid in its turn controlled the valve by which water was admitted to the turbine. If the load diminished and the main current increased, the solenoid caused this valve to close, thus diminishing the power supplied to the exciter and lessening the current supplied to the field-magnets of the generators, whose P. D.'s at once fell, and the main current regained its normal value. The action was the opposite when the load was increased.

For higher voltages the machines were self-exciting, and each carried a mechanical regulator electrically controlled. From full load to three-quarters load the regulator acted upon a resistance in the field-magnet circuit; but from three-quarters to no load its action was transferred to the brush gear, which it rocked so as to diminish the effective voltage of the machine. Carbon brushes were used.

For reasons which it may be possible to discuss fully later, the system of transmission of power by continuous currents at high voltages has not been very widely developed, but there is a notable instance of it in the neighbourhood of London elaborated by Mr. J. S. Highfield,

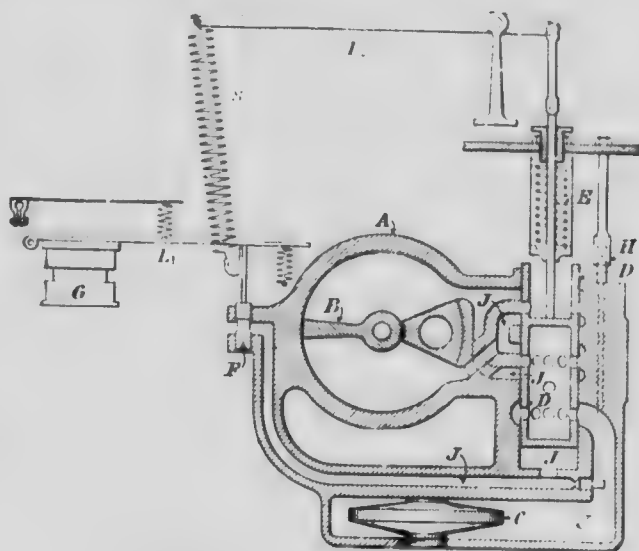


Fig. 191—Thury's **gulator for Shifting the Brushes.**

under the auspices of the Metropolitan Electric Supply Company, as suitable for a sparsely populated district. It will be sufficient for our present purpose to describe the developed type of Thury regulator as used thereon.

In the earlier types of regulators referred to above, the necessary movements for the introduction of resistance or changing the position of the brushes were made by the armature of an electro-magnet actuating pawls

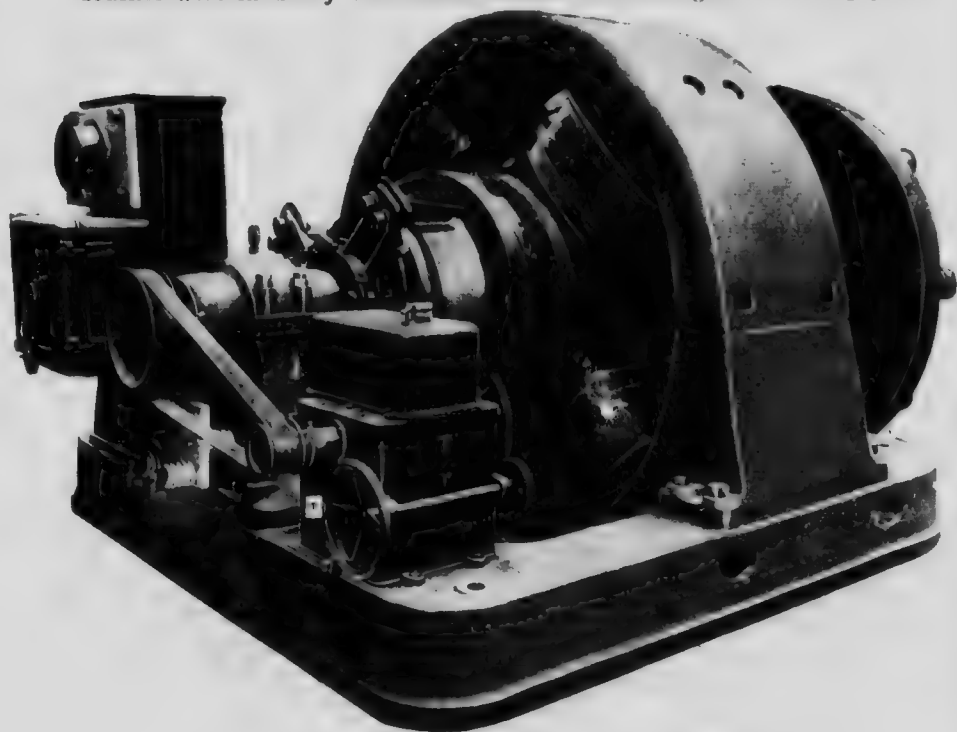


Fig. 192.—5,000-volt d.c. Dynamo, with Thury Regulator for Shifting Brushes.

and gearing by which the required motions were transmitted to the operating shaft or shafts. In the more recent method adopted in London the energy required to rotate the shafts is derived from a small hydraulic turbine working in oil and driven from the shaft of the machine to be regulated. This turbine maintains the oil in the turbine, and its casing at a pressure of 2,000 lbs. per square inch. The regulation is accomplished by the intervention of a solenoid which admits the pressure oil to a gate working on a shaft. The solenoid operating the admission gate so that the oil is admitted to turn the gate either one way or the other as may be necessary.

With this preliminary explanation it will not be difficult to follow the actual details of the regulator, a diagrammatic horizontal section of which is given in Fig. 191. The apparatus mounted on the bed plate of a 5,000-volt motor, built by Messrs. Dick, Kerr & Co., is shown in Fig. 192, the method of control is of course the same whether the regulator is applied to a dynamo or a motor. In Fig. 191 the controlling solenoid is indicated only at G the plunger, the end of which only is shown acting on the levers L_1, L_2 against the springs s and E . At the other end of the system is the turbine C completely immersed in oil and driven by a belt, seen in Fig. 192, from the shaft of the machine to be regulated. The function of this turbine, as already explained, is to maintain a pressure of 25 lbs. per square inch in all parts of the oil J, J, J contained in the passages, etc., of the casing. The operating cylinder A is vertical, and contains a gate B , which can be rotated on a vertical shaft through a segment of the cylinder. The oil under pressure can be admitted to either side of this gate according to the position of the small piston valve D which is controlled by the solenoid G . The vertical shaft of B is geared by bevel wheels to a horizontal shaft which acts directly on the brush rocker. A toothed-wheel segment T , attached to this shaft for hand operation, can be seen in Fig. 192. Thus any variation in the current through the solenoid G changing the direction of the flow of oil brings into play a very large force quite sufficient to rock the brushes, and also to operate a switch which shunts more or less of the excitation current in the field magnets. When, in addition, it is explained that the brush rocker is mounted on roller bearings the remoteness of the possibility of failure will be understood. The small springs shown in Fig. 191 are introduced to prevent hunting. The action is rapid, for it is claimed that the necessary adjustments between no load and full load can be made in less than one second.

IX.—SIZE AND OUTPUT

By the "output" of a dynamo is meant the maximum amount of power measured in watts (or kilowatts) which may be taken electrically from its terminals for long periods of time without unduly heating or otherwise damaging the machine. If more power than this be taken the dynamo is said to be "overloaded," and most modern machines, especially those built to supply power for traction purposes, are so designed that, without serious trouble, they can take a considerable "overload" for a short time. The rated "output," however, should always be the maximum safe load which the machine can carry for several hours without showing signs of distress. To test this point it is usual to specify a maximum excess temperature, beyond which the temperature of the machine must not rise when run for several hours at the specified full load. Incidentally, it may be remarked that this excess temperature gives

a rough indication of the efficiency of the machine, that machine, *ceteris paribus*, being most efficient which keeps coolest during a long full-load run.

The connection between the output and the size or dead weight of the machine is an important one for the builder to consider, and is also of interest to the user. It is intimately bound up with the speed at which the dynamo may be run, for, as we have already pointed out, the higher the speed the lighter will be the machine for a given output, and therefore the less costly, at any rate as regards materials.

With so many variable quantities in the design, and so many new conditions to be fulfilled as the size increases, it is not to be expected that theory will be able to give more than a rough indication of the connection between size and output, and then only under carefully defined conditions. Attempts have therefore been made, by examining the data obtained from various machines after construction, to find empirical laws which fit the available figures. For instance, taking machines working within safe temperature limits, Jackson deduced the equations

$$\kappa = .002 w^{.16} \text{ (between 5 and 25 kilowatts)}$$

$$\text{and} \quad \kappa = 5 + .0059 w \text{ (above 25 kilowatts)}$$

where κ is the output in kilowatts and w is the weight in lbs. These equations mean that if the data for κ and w be plotted on squared paper the line obtained will be curved near the origin (to $\kappa = 25$), and then straight for large machines.

On the assumption that the output of a set of similar machines varies with the cube of the linear dimensions (*i.e.* practically with the weight), Dr. Hopkinson showed that the electrical efficiency (*see* page 515, Vol. I.) of large machines would be greater than small ones, but that the gross efficiency would not show a corresponding increase, because of greater eddy current losses. An examination of actual machines shows that Dr. Hopkinson's assumption can only be made where the machines compared are strictly similar, the larger machines being run at a lower speed of rotation, so as to avoid danger from centrifugal forces.

Kapp, on the assumption that the speed (revolutions per minute) should vary inversely as the linear dimensions, and that the temperature rise for a long run was to be the same in all the machines, showed that the output would vary as the $3\frac{1}{2}$ th power of the linear dimensions, or

$$\kappa \propto r^{3.5},$$

where r is the *ratio* of the linear dimensions of the machines compared.

That the centrifugal forces per unit mass should be the same at the periphery of similar revolving bodies, requires that the speed should vary inversely as the square root of the ratio of the linear dimensions. On the assumptions that these centrifugal forces are to be the same for all sizes of machines and that the rise of temperature at full load is also to be the

same, the writer finds that the output should vary with the cube of the linear dimensions—that is, with the weight.

The problem is simplified if we confine our attention to the armature, for we then get rid of the variations in the types of field magnets used to produce a given mean flux density (**B**) under the poles. Considering only the armature and the speed, Snell, and also Esson, deduced the equation

$$K = k l D^2 n \quad (1)$$

where l and D are the length and diameter of the armature and n is the speed. The value of k was found to be 0.00001 for ring-wound armatures and 0.000015 for drum-wound armatures if l and D be measured in inches and n in revolutions per minute. The actual value of k necessarily depends on the flux density in the gap, and the ratio of pole arc to pole pitch.

For practical purposes, it is usual for designers to employ the reciprocal of k in the above formula, which may be re-written

$$D^2 l = \frac{1}{k} \times \frac{K}{n} = \kappa \times \frac{\text{kilowatts}}{\text{R. P. M.}} \quad (2)$$

It is in this form that the multiplier κ is most frequently known as the *output coefficient*; though nominally a constant, it is not really so, being much larger for very small machines than for big multipolar modern dynamos. As might be expected when deduced for a series of machines of the same type, it is more constant than when found for machines of widely different types, but even in the former case, it decreases at first rapidly, and then gradually as the size increases. For instance, in a certain line of machines of the same type, κ fell from 100,000 to 46,000 as the size increased from 5 to 50 kilowatts, after which the fall was practically regular, the value dropping gradually to 30,000 at 300 kilowatts.

The dependence of the output coefficient k , as it appears in equation (1), on the size of the machine and also on the speed is given in the curves in Fig. 193, which is taken from a paper by Messrs. Hobart and Ellis, which appeared in the *Electrical Review* in 1907. The output coefficients are plotted vertically, and the rated outputs horizontally. The vertical scale must be multiplied by 0.0000164 to obtain the actual coefficients in the

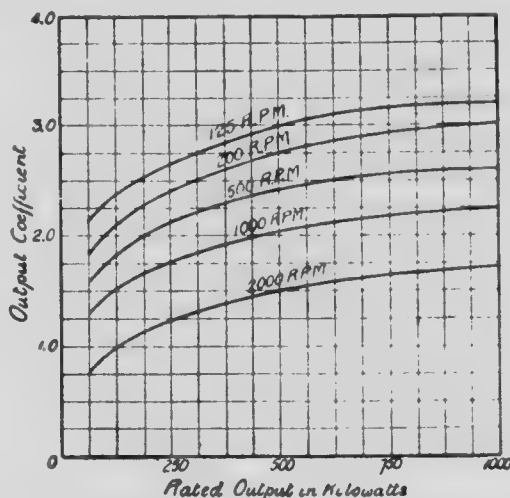


Fig. 193.—Output Coefficient Curves for 500-Volt Machines at Various Speeds and Outputs.

units previously used in connection with equation (1). The curves show very strikingly how the increase of speed diminishes the value of k (and therefore increases the value of κ in equation (2)); they also give more recent values of the coefficients, based upon standard modern practice.

It will be noticed that in equation (2) the left-hand side is proportional to the volume of the armature, and if κ were really a constant the equation would mean that the output per revolution is proportional to the volume of the armature, which may therefore be regarded as the basis upon which

Snell and Esson founded their rules.

How nearly this condition of proportionality is attained in practice can be gauged from Fig. 194, taken from a paper by Messrs. Macfarlane and Burge, read before the Institution of Electrical Engineers in 1908. The abscissæ or horizontal ordinates give the values of $D^2 \times l$, and the vertical ordinates the watts (not kilowatts) per revolution per minute.

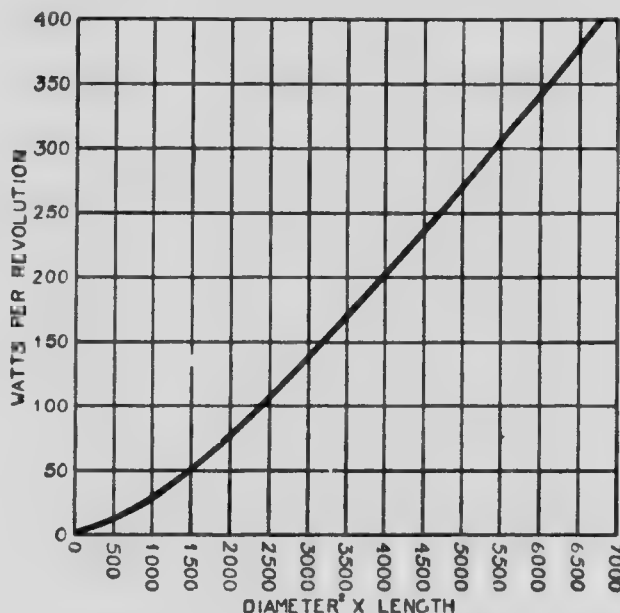


Fig. 194.—Relation between Volume of Armature and Output per Revolution.

The upper part of the curve is fairly straight, but towards the origin it bends somewhat sharply. At 50 watts per revolution the value of κ (equation (2)) for this curve works out at 30,000, whilst at 400 the value is 17,000. The data for the curve are taken from small square pole-face machines of the best design at the time of the reading of the paper.

An entirely different basis is taken by Steinmetz, who, neglecting the speed, uses an empirical rule, based on the assumption that the output is proportional to the cylindric surface of the armature or

$$D \times l = \sigma K \quad (3)$$

In this formula the constant or co-efficient σ is known as the *Steinmetz output coefficient*. The physical basis is obviously that the cylindric surface of the armature, being the principal radiating surface for getting rid of the

heat generated, and thus keeping the armature cool, and further regarding this radiated heat as a definite percentage of the kilowatt load on the armature, the two must be proportional to one another for a given safe limit of excess temperature. The argument further implies a standard flux density, and a recognised safe peripheral speed for the armature, as speed does not directly appear in the formula.

With D and l measured in inches, and K in kilowatts, the usual value of σ in equation (3) is somewhere about 3, but for reasons similar to those given for the variation of the output coefficient in equation (2), σ varies for different types and sizes from about 2.3 to as high as 6 or higher, and there may be exceptional cases outside these limits.

In 1898, Sumec showed that the output w in watts may be expressed by the formula

$$w = \frac{l D^2 n c B b \pi^2}{10^8} \quad (4)$$

where the additional symbols introduced are

c = current in amperes per centimetre length of armature circumference.

b = $\frac{\text{width of pole face}}{\text{pitch of poles.}}$

By the "pitch" of the poles is meant the linear distance, measured along the circle, from the centre of a pole face to the centre of the next pole face. In this formula the design of the field magnets is not taken into account.

Effects of Current and Voltage.—It will be noticed that in the foregoing remarks the reference is to the output in *kilowatts* only, and that no attempt is made to distinguish between machines giving a large current at a low pressure and machines giving a small current at a high pressure. This is because the *power* required is the principal factor, and because to some extent it is possible to wind a given armature carcass with many small conductors to give a high voltage, or with a small number of heavy conductors which will only produce a low voltage, but will carry safely a much heavier current than in the former case.

In extreme cases, where the currents are very heavy or the voltages very high, modifications are rendered necessary by difficulties of commutation or of insulation, and even within narrower limits some differences in design are advisable; but as a broad rule it is correct to say that it is the *power* which has to be handled, combined with the speed, which fixes the gross size of the machine, and not the particular electrical form in which that power is to be delivered.

There is one way of increasing the output which, at first sight, appears to offer distinct advantages. Suppose we have a dynamo designed to give a certain E. M. F. and current at a certain speed with a given magnetic flux through the armature and a specified number of conductors on the

armature, if we can take a larger current from the machine without altering any of these quantities we shall increase the output. The first difficulty to be met is the extra heating of the machine, which, if overloaded in this way, will soon become dangerously hot. To reduce this it will be necessary to use thicker (or radially deeper) conductors on the armature, and to make room for these either the gap space must be widened in smooth core machines or the slots deepened in toothed armatures. In the first case the widening of the non-magnetic gap will necessitate increased excitation and lower the efficiency, but more serious still, because of the increased ampere-turns on the armature, the reactions (*see* page 100) will be increased, and a point will soon be reached at which sparkless commutation becomes impossible. In the second case the same results are reached in a slightly different way. The deeper burying of the conductors will necessitate increased excitation if the coil be left otherwise unchanged, and the rapidly increasing inductance of the coils short-circuited on the commutator will soon render sparkless commutation impossible. Put shortly, therefore, this apparently simple method of increasing the output is barred both by lower efficiency and by difficulties of commutation. The latter point is the more important one.

In the last edition of this book (*see* pages 830 and 831) particulars of over seventy machines were tabulated to enable readers to gauge how far the foregoing formulæ give results borne out by practice. The curves just given (Figs. 193 and 194) will probably be found more useful, but readers who are interested in the development of the subject might consult the table, as there are included in it machines from the earliest times down to the machines which had then but recently come into use. An interesting feature is the weights per kilowatt of the armatures of the machines examined. For many and very diverse examples these weights ranged from about 28 lbs. to 36 lbs. per kilowatt, whether the machine were multipolar or bipolar, or whether it were a slow-speed or a high-speed dynamo, turbodynamos not being, however, included in the table, as at that time they were comparatively unimportant. As might be expected, the armature weight per kilowatt was found to vary within narrower limits than the gross weight per kilowatt.

Standardisation.—In all cases where great numbers of similar machines have to be made, the cost of production is very much reduced if standard patterns can be adopted for the various sizes required, and to fulfil the varied conditions under which the machines have to be used. It is therefore the aim of every manufacturer to select a few sizes and conditions—but the fewer the better—sufficient to satisfy the demands of his customers, and to adapt his patterns, tools, jigs, etc., to the production of these standard machines, as they are called, at the lowest possible cost. In the design of each machine the best manufacturers make as many of the parts as

possible interchangeable, thereby lessening not only the first cost, but the cost of repairs and renewals, and it is sometimes possible to make some of the minor parts interchangeable, not only between machines of the same size and design, but also between machines of different sizes in the same "line" of standardisation.

When the problem of dynamo and motor design is attacked from this point of view a slight examination of the very varied conditions of output, speed, voltage, and current which are demanded by different users almost makes the designer despair of any real advance towards standardisation unless the users agree to be content with two or three standard voltages and speeds as being applicable to large sections of work. Even then, remembering that the machines must be of different sizes, the number of different "standards" required is greater than most manufacturers would care to stock. Mr. Hobart has calculated that with twelve sizes from 2 to 75 H. P., with only three voltages, with two speeds (high and low), with two types (open and enclosed), and the ordinary series and shunt windings usually demanded, 360 different ratings would be required.

In considering the subject of standardisation it is sometimes assumed that the only difference that need be made between machines of different voltage for the same output is in the cross-section of wire to be wound on the armature, and probably also on the windings of the field-magnet coils, to give the same number of ampere-turns with the altered voltages or currents. Within small limits the assumption is justifiable, but these limits are smaller than is often supposed.

Thus, as the voltage is pushed higher and higher, the number of commutator segments must be increased so that the voltage between successive bars, and especially the inductance per section, upon which sparkless running depends so much—may not be excessive. But sooner or later a limit in the increase of the number of commutator sections will be reached at the least practicable thickness of the individual bars. To proceed farther in this direction would then necessitate an increase in the diameter of the commutator, which might involve in practice the designing of a new machine. Since, however, the currents diminish for the same output in the same proportion that the voltage rises, a less axial length of commutator will suffice for the narrower or less numerous brushes which can be used at high voltages. The axial length thus saved on the commutator can be added to the armature without altering the bed plate, pedestals, bearings, or shaft of the machine. This increased length of armature will involve a corresponding increase in the axial length of the magnet poles and frame, and with the same number of poles the flux per pole will be increased, and the voltage will therefore be obtained with fewer turns per section of the commutator and with less inductance.

Other considerations point in the same direction, so that we reach the

conclusion that machines of the same output may, within wide limits have the same over-all dimensions, but that for large currents at low voltages the armature should be axially short and the commutator long (see Fig. 157), whereas for small currents at high voltages the axial length of the armature and that of the short.

This result vocated by Mr. to whom the 196, and 197 are due. In machine is for 100 kilowatts tions per terminal P. D.'s and 550 volts each machin pedestals, bear- are of the same also are the dia- armature and tor. Whilst,

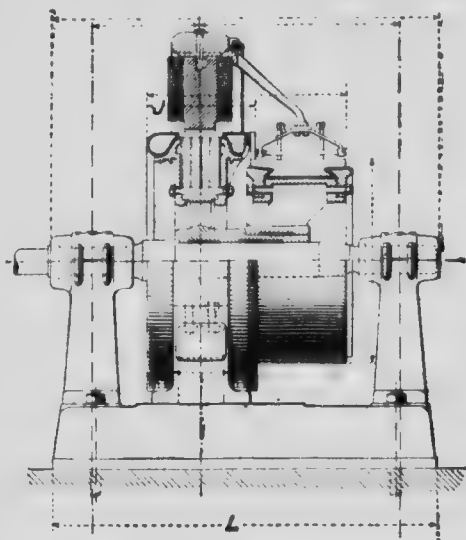


Fig. 195.—For 115 Volts, 270 Amperes.

is strongly ad- H. M. Hobart, three Figs. 195, illustrating it each case the an output of at 500 revo- minute, but the are 115, 230, respectively. In the bed-plate, ings, and shaft dimensions, as meters of the the commuta- however, the

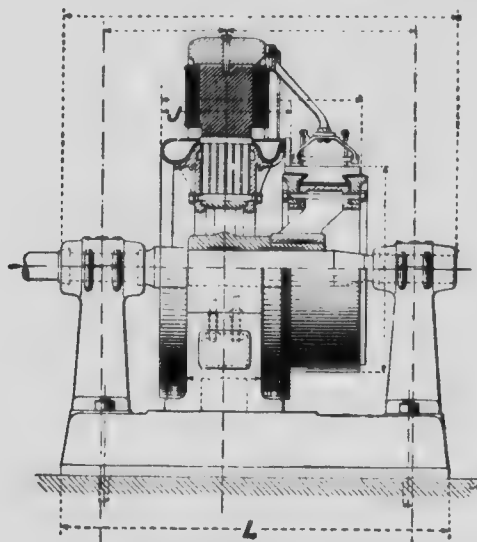


Fig. 196.—For 230 Volts, 435 Amperes.

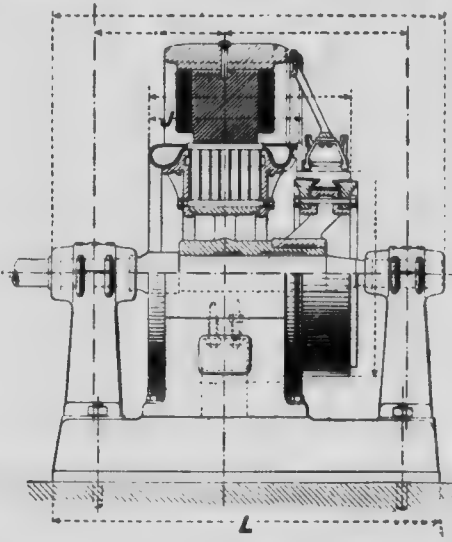


Fig. 197.—For 550 Volts, 182 Amperes.

Dynamos of the Same Output but of Different Voltages.

axial length L of the combined armature and commutator is the same—namely, 71.0 cms.—in all three cases, this length is differently apportioned to the two parts in each machine. In Fig. 195 the part marked J is 39.5 cms., and the length of the commutator face is 31.5 cms. In Fig. 196, where the voltage is doubled, these dimensions are 47.0 and 23.0 respectively, whilst in Fig. 197 at 550 volts they are 55.0 and 16.0 cms. The numbers of commutator segments in the three cases are 408, 432, and 570, whilst the numbers of the armature conductors are 816, 864, and 1,140, giving in each case two conductors or one complete turn per armature segment. The same armature stampings cannot be used for each case, as the slots differ in number and size, though not very greatly. Although for the same variable parts the patterns are not identical, and for the lowest-voltage machine the number of poles is increased, Mr. Hobart claims that with care and ingenuity it is practicable "to arrange to use the same drawings and substantially the same patterns, the latter being arranged for special modifications by being extended and shortened for the different voltages."

X.—TYPICAL AND SPECIAL MACHINES

In the preceding parts of this chapter, and in the earlier volume of the book a number of continuous current dynamos of many different types have been more or less fully described and used to illustrate the numerous interesting points which are involved in the design and construction of a modern machine. It is, therefore, not necessary to devote much further space to the description of complete machines, but it will not be uninteresting in conclusion to refer briefly to one or two recent examples built by well-known manufacturers, and also to some machines built for special purposes.

Modern Continuous Current Machines.—Although, as already explained, the modern tendency in dynamo production is in the direction of large units for central station work there still exists a demand for smaller sets of isolated plant for use where no public supply is available. Most firms of dynamo builders therefore produce complete sets of prime movers and generators mounted upon a single bedplate. These sets are quite self-contained if internal combustion engines are used as prime movers, but where steam engines are employed the necessary steam-raising plant is required in addition. From a great number of available examples the following are selected.

In Fig. 198 we have a set designed by Messrs. Crompton and Co., in which a dynamo is driven by a high-speed oil engine, and which is therefore quite self-contained, and only requires to be supplied with the necessary fuel in the form of suitable mineral oil. The set when running at 800 R. P. M. is capable of giving an output of 150 amperes at 75 volts or 11.25 kilowatts. The dynamo is a four-pole machine of the type of which particu-

lars have been given in other parts of the book (see pages 156 and 157); it is fitted with the neat brush gear fully described at page 156, and is direct coupled to the oil engine, one of whose bearings is utilised to support one end of the dynamo shaft. Between the two machines there is a comparatively heavy fly-wheel whose function is to counteract the fluctuations of the speed of the oil-engine due to the intermittent character of its im-

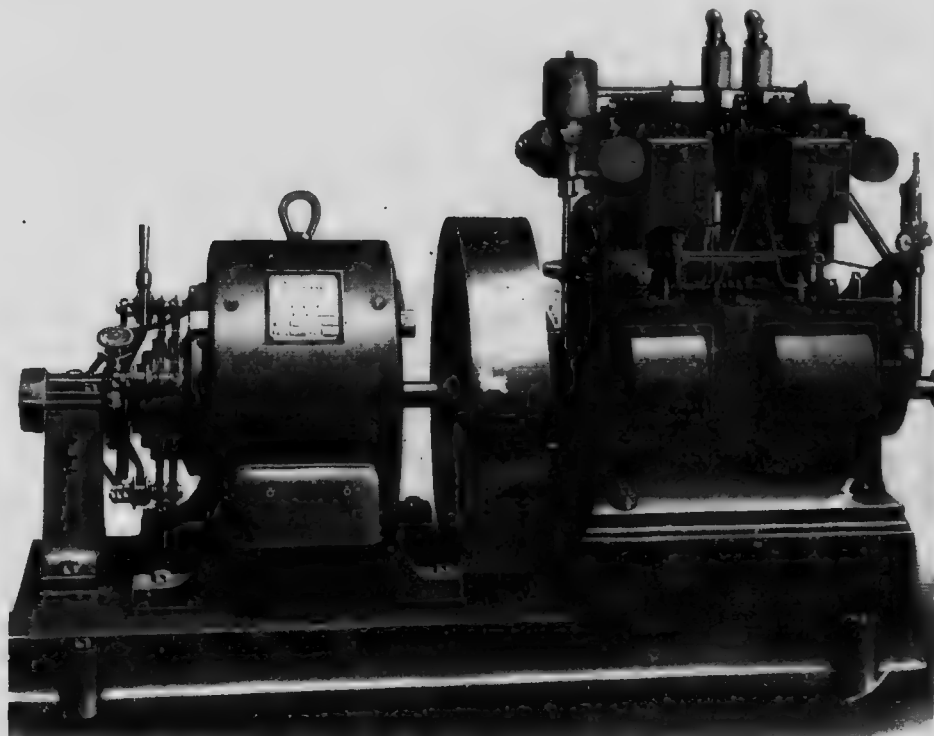


Fig. 198.—Crompton's Self-Contained 11½-Kilowatt Set.

pulse. This fly-wheel at full speed stores 29,500 foot-pounds of energy. The total floor space occupied by the set is 6 ft. by 2 ft. 8 in., and the over-all height is 3 ft. 10 in.

For the same output in kilowatts the machines can be wound for various voltages and the corresponding currents, the standard voltages being 100, 135, 220, 440, and 500 volts. The 135-volt machine is specially designed for charging batteries on a 100-volt installation, and it will work in parallel with the battery at any p. d. between 100 and 135 volts without change of speed, the voltage regulation being obtained by a resistance in the field

excitation circuit. When used for heavy current work at correspondingly lower voltages than the above the armatures are wound with stranded bars



Fig. 190 — Multipolar Dynamo, 500 Kilowatts, of the Société Gramme

and cables, the strands being twisted with a short lay as previously described, thus killing the eddy currents in the copper (see page 60).

Modern Multipolar Dynamos.—An interesting example of a multipolar

machine built by the historic Société Gramme is shown in Fig. 199 which represents a machine built to give 500 kilowatts at 125 R. P. M. The machine has an external diameter of 138 inches, the diameter of the rotating armature being 98.5 inches. The armature is of the drum-wound type, and has the conductors placed in slots in which they are held by hardwood wedges, and are joined to one another and the commutator in the usual way. The commutator itself is 49 inches in diameter, and is carried by a substantial

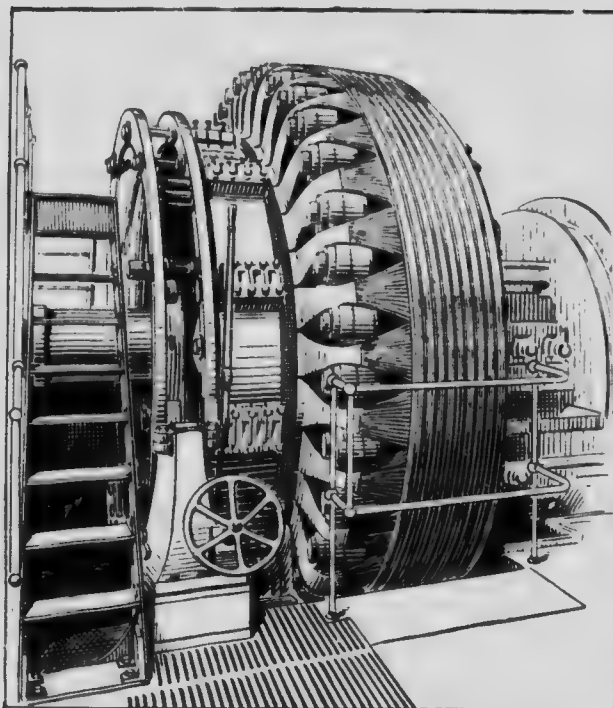


Fig. 200.—Multipolar Dynamo, 1,500 Kilowatts, with External Armature.

spider, keyed to the shaft and in one piece with the armature spider. The brush gear and rigging are carried by six substantial brass brackets attached to the yoke ring of the machine, and supporting a fixed ring, which grips at six places the inner rings, which can be rotated by the screw and hand wheel seen at the side. These adjustable rings carry the twelve collectors, each of which in its turn carries the carbon brushes. The

total current is 2,000 amperes at 250 volts, which gives 335 amperes per collector, or not more than 50 amperes per square inch of section in the brushes.

The multipolar dynamo shown in Fig. 200* is an interesting and now historical example of the development of a particular type. It was built in 1899 by the Siemens and Halske Company of America for the West Chicago Street Railway Company to equip further a station in which the earlier machines were similar to the machine shown in Fig. 511 (Vol. I.) in the historical section. In both machines the revolving armature is external

* From the *Street Railway Journal* of New York, Vol. XV., page 429 (1899).

to the fixed field magnets, and in the earlier machines the external wires of the ring-wound armature were used for commutator bars. Owing to the high speed of the outer periphery of the armature, which in Fig. 511 is 3,300 feet per minute, difficulty was experienced in keeping the bars in position, as the method of construction did not permit the usual binding

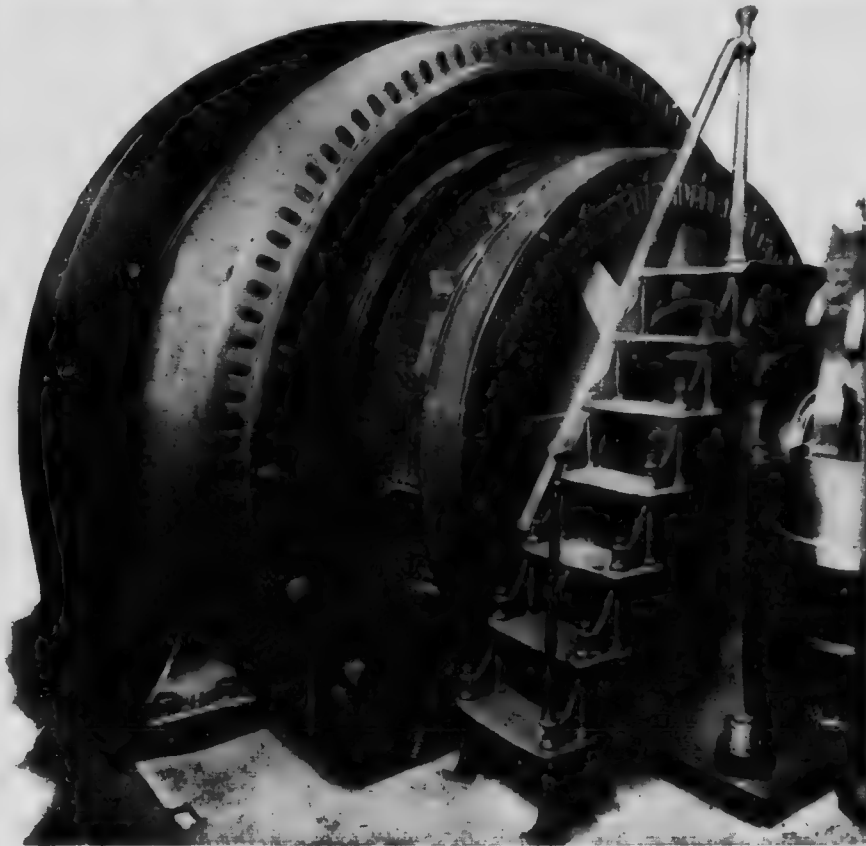


Fig. 201.—1,000-Kilowatt Dynamo of the International Electrical Engineering Company.

wires, and, therefore, in the later machines a separate commutator of less diameter than the armature has been provided. The modification involves the bringing of numerous connections down from the armature to the commutator lugs, and these connections can be seen in the figure grouped in bunches where they pass over the driving spider between the ends of the gun-metal driving arms. The change thus rendered it possible to run binding wires round the armature to assist in keeping the conductors in place. The dynamo was designed to develop 1,500 kilowatts, or 2,700

amperes at 550 volts at a speed of 75 R. P. M.; the outside diameter of the armature was 14 feet, and the shaft 28 inches in diameter at the spider and 22 inches at the bearings, which were 46 inches long. To steady the engine under the sudden changes of load met with in tramway work, a flywheel weighing 80 tons was mounted on the shaft

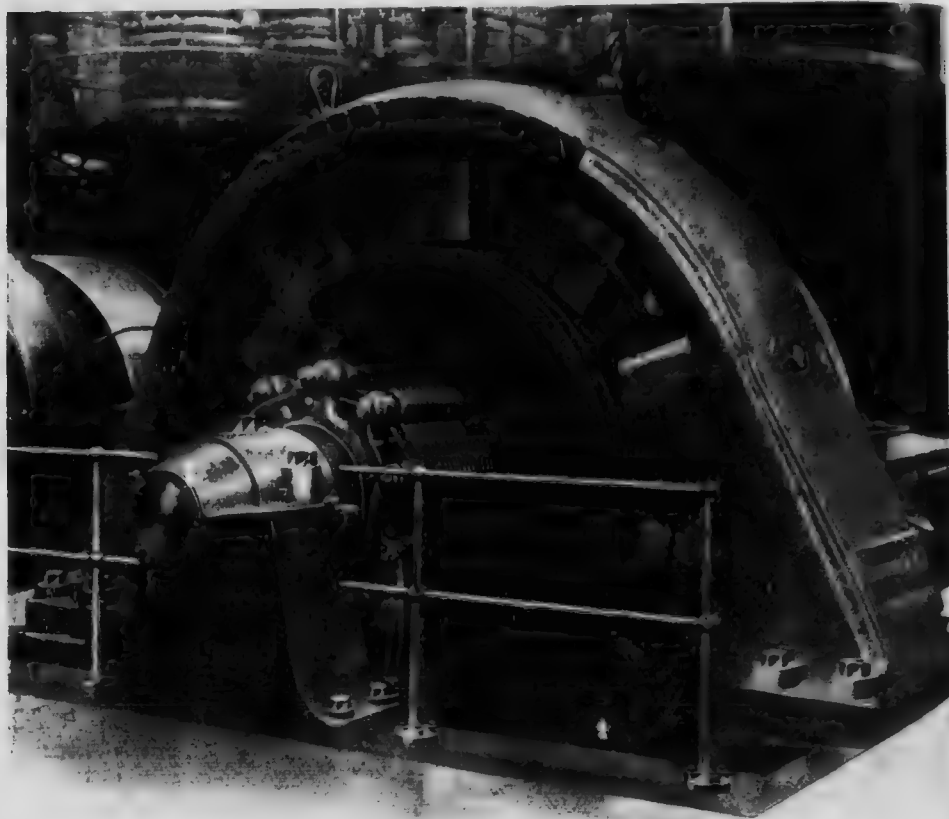


Fig. 202.—Crompton 750-Kilowatt Dynamo (See also Plate III.).

The completed dynamo, the armature of which was shown in process of construction in Fig. 70, is illustrated in Fig. 201. It is a dynamo constructed by the International Electrical Engineering Company for the Brussels Central station, and is designed to give an output of 1,000 kilowatts or 3,850 amperes at 260 volts when running at a speed of 85 R. P. M., which is the speed of the Van der Kerchove engine by which it is driven. The machine has an over-all diameter of 105 inches, whilst the diameters

of the armature and commutator are 118 and 94.5 inches respectively, the peripheral speeds being 2,760 and 2,170 feet per minute. There are 18 poles, and each of the 18 brush holders carries nine carbon brushes, of which therefore there are 162 altogether, each collecting on an average about 23 amperes. The total number of armature conductors (see Fig.

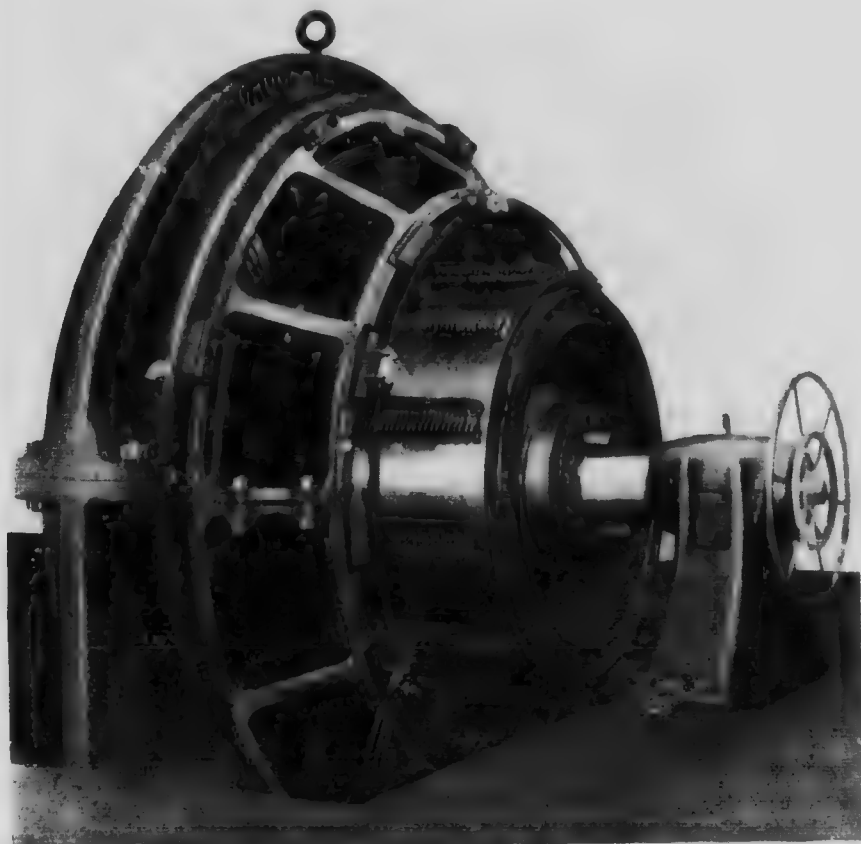


Fig. 203.—Cocker-Wheeler 900 Kilowatt Dynamo.

70) is 1,440, or 80 to each pole. The total weight of the machine is 34.5 tons. The armature weighs 15 tons, but in machines thus driven directly by slow-speed engines it is absolutely necessary to employ a flywheel, as the slowly-moving armature has not sufficient mass at these low speeds to store the necessary kinetic energy.

A large modern multipolar machine built by Messrs. Crompton and

Co. is shown in Fig. 202, and fuller details are given in Plate III., to which reference has been made elsewhere. It has ten poles, and is designed for an output of 1,650 amperes at 450 volts, at 250 R. P. M., but can be loaded up to 900 kilowatts without overheating. The magnet yoke ring is of steel, and has an over-all diameter of 10 ft. 4 in., whilst the pole faces are bored to a diameter of 6 feet. Full particulars of the armature will be found on page 85 and of the brush gear on page 155. The bearing, details of which can be clearly seen in Plate III., is self-oiling, and has a diameter of 8 inches,

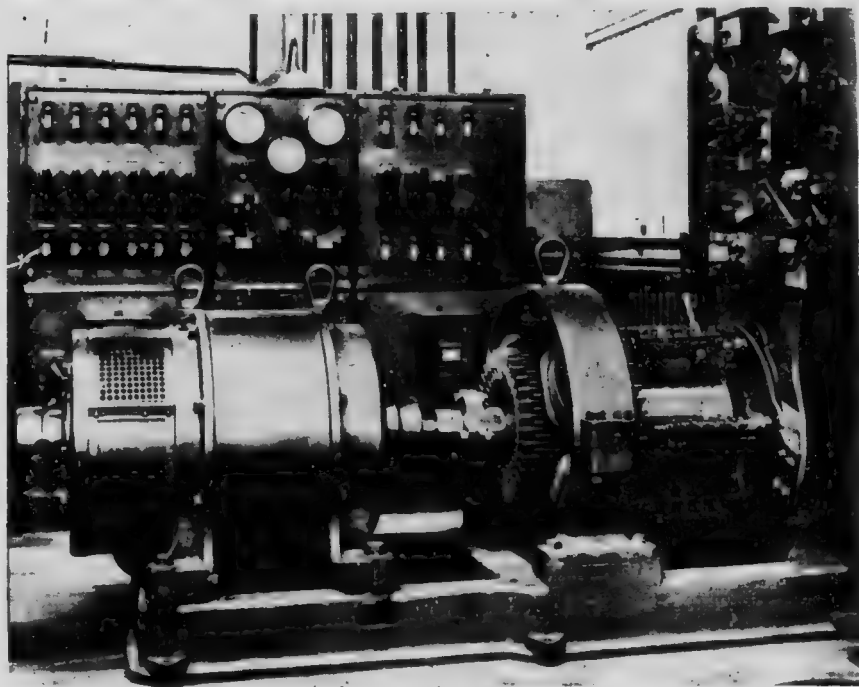


Fig. 204.—Crompton Small Low-Voltage Dynamo Set.

the bush being of cast-iron lined with white metal. The complete armature weighs 8 tons, and the whole machine 21 tons.

As a further example of a modern continuous current generator, Fig. 204 depicts a 900-k. w. machine, built by the Crocker-Wheeler Company of New Jersey. It is designed to give an output of 3,750 amperes at 240 volts, when running at a speed of 160 R. P. M. The machine has twelve poles, its armature, weighing 11.4 tons, being 87 inches and its yoke ring 148 inches in diameter. It is interesting to compare this specimen of American practice with the preceding machine of the same total safe output by a well-known English firm, but in making the comparison it

must be remembered that although both machines give the same total output, the English machine runs at a higher speed and gives current at 450 volts as against the 240 volts of the American machine. The latter has therefore to handle double the current of the former, a fact which should be kept in mind in comparing the commutators and the brush gear. Both machines are provided with interpoles, but there are many interesting differences in details of design which the reader should note. The light wheel with six spokes shown outside the bearing of the American machine is part of a speed-indicating arrangement used when testing the machines.

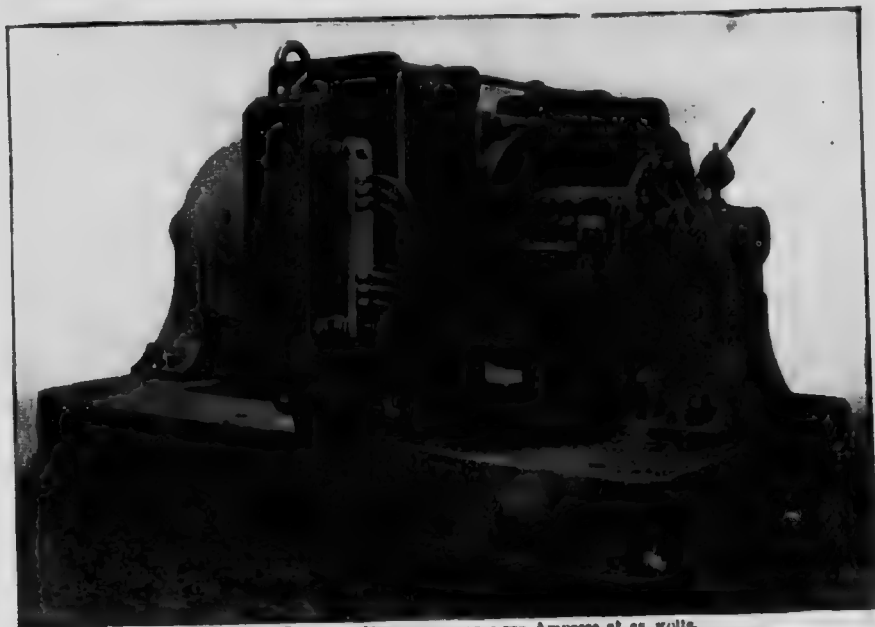


Fig. 205.—Crompton Dynamo giving 3,000 Amperes at 25 volts.

Dynamos for Electrolytic Work.—For electro-chemical, electro-metallurgical, and for electrolytic work generally, electrical energy is required in the form of heavy currents at low voltage. This requirement, as has been already pointed out more than once, modifies the design of the machine, more especially on account of the arrangements required for commuting the heavy currents which have to be handled. On page 156 attention has been drawn to the great increase in the length of the commutator as compared with the axial length of the armature in a machine built by Messrs. Crompton and Co., Limited, for heavy currents at a low voltage, the output being 3,000 amperes at 2 to 8 volts, or about 400 amperes per volt. A machine in which the voltage is still lower is shown in Fig.

204, which represents a six-pole dynamo constructed by the same firm to give 3,000 amperes at 1 to 4 volts, or over 800 amperes per volt, when run at a speed of 400 R. P. M. If required the dynamo can be overloaded to the extent of giving 4,000 amperes for one hour without damaging the machine. The chief interest centres in the commutator and the brushes, the arrangement of the latter being clearly shown in the figure. For reasons previously given the machine is not self-exciting, an exciting current of 8.6 amperes at 100 volts being taken from the supply mains which convey energy to the driving motor. This provides an excitation of 4,200 ampere-



Fig. 204.—Westinghouse Double-Commutator Armature for Electrolytic Work

turns per pole, and it will be noticed that the energy used in the field-magnet circuit is only 7.3 per cent. of the full load output of the machine. The heavy flexibles by which the current is carried to the terminals and the massive character of the latter should be specially noted.

A still larger machine, though of somewhat older pattern, built by the same firm, for electro-chemical work, is shown in Fig. 205. This machine has an output of 75 kilowatts, giving 3,000 amperes at 25 volts, or 120 amperes per volt, a lower ratio than in the smaller machines just described. In this case the dynamo has four poles, and therefore four sets of collecting brushes, each consisting of six copper brushes. At full load each of these brushes transmits a current of 250 amperes, the total current per set being 1,500 amperes, which is carried direct, collecting rings being dis-

pensed with, by six heavy flexibles to the massive terminal blocks at the side, where the brushes of similar polarity are paralleled. The armature is about 30 inches in diameter, and has a smooth core; it is wound with two windings, each consisting of 64 conductors, made of No. 18 wire in 117 strands, twisted and compressed to a rectangular section. This gives a current density of 1,700 amperes per square inch in the copper, which is not excessive. The machine is self-excited.



Fig. 207.—Westinghouse Double-Commutator 4,000 Amperes, Low Voltage Dynamo.

One device which is employed to meet the difficulty of the long length of commutator required for the collection of these heavy currents is to build the armature with two commutators, one at each end, and to wind the machine with two separate but interleaved circuits, each connected to one of these commutators. An example is given in Figs. 206 and 207, which show respectively the armature and a complete machine of this type built by the British Westinghouse Company. The dynamo is intended to give an output of 4,000 amperes at 90 volts or 360 kilowatts

at a speed of 250 R. P. M. It stands 99 inches high, is 91 inches wide, and the shaft from the outside of the bearing at one end to the coupling flange at the other is 120 inches long. There are twelve poles, and the brush gear is of the same design as that which has already been described at page 164 (Fig. 163). In that case the brushes had to collect 4,250 amperes on a single commutator, and there were 16 sets of 8 brushes each, or 128 brushes in all. In this case each commutator deals with 2,000 amperes

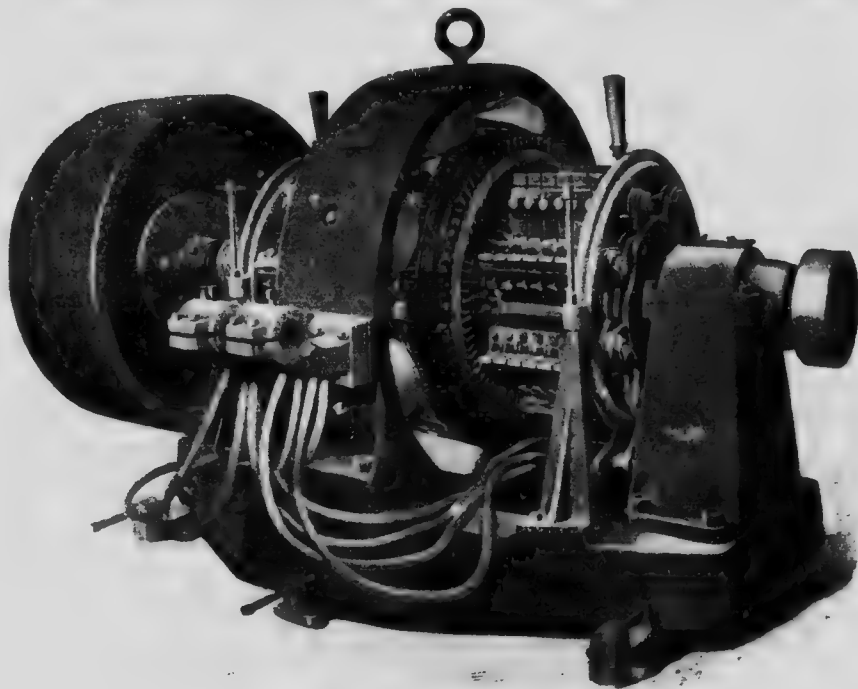
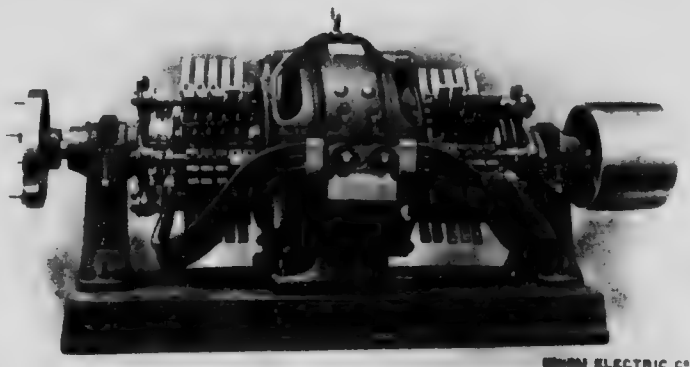


Fig. 208.—Eddy Double-Commutator Dynamo, 4,500 Amperes at 20 Volts.

only, and the brushes are reduced to 12 sets of 5 brushes each, making 60 brushes for each commutator, or 120 brushes in all. The number of individual brushes is therefore nearly the same in the two cases. But in the present case the machine has less than one-half the output in kilowatts, though the amperage is nearly the same, and therefore it is smaller than the previous machine, and has a commutator correspondingly smaller in diameter. To place the 120 brushes on this smaller commutator would have necessitated lengthening it to make room for 10 brushes per set, and the rods of the collectors, already somewhat long in Fig. 163, would have become excessively long and clumsy. Hence the desirability of in-

curing the expense of an additional commutator with its separate brushes and brush gear.

Another example of a double commutator dynamo is given in Fig. 208, which represents a 90-kilowatt dynamo built by the Eddy Electric Manufacturing Company, and designed to give 4,500 amperes at 20 volts for electrolytic work. Each commutator, therefore, dealt with a total current of 2,250 amperes, or 112.5 amperes per volt. The machine had eight poles only, and arrangements had to be made to collect the 4,500 amperes on commutators of still smaller diameter than those last described, which had to deal with only 22 amperes per volt. Copper brushes were used, each brush being capable of carrying a larger current than could be collected by a carbon brush of the same width. Each brush holder carried



EDDY ELECTRIC CO.

Fig. 209.—Low-Voltage 12.5-Kilowatt Dynamo, giving 2,500 Amperes at 970 E. P. M.

6 brushes, and as there were 16 brush holders on the two commutators the total number of brushes was 96, which works out to 94 amperes per brush at full load as against 66 amperes per brush in the previous case.

The brush gear, instead of being supported from the yoke ring, as in the preceding examples, was in this case carried by the pedestal. From the collecting rings the current was led by heavy flexible cables to large terminals fixed to the yoke ring of the machine. Each commutator had its own separate terminals, one on either side of the machine, and it was therefore possible to connect the two armatures in parallel to give 4,500 amperes at 20 volts, or in series to give 2,250 amperes at 40 volts. Further, for distribution to the baths the armature could be connected to a three-wire system, from which currents at 20 or 40 volts could be drawn, as might be required. In this way a very appreciable saving in the cost of the distributing conductors was realised.

In these machines the armatures are slotted and bar wound, and the

field magnets for the larger sizes are separately excited. This plan of separate excitation, as explained above, is found advantageous for low-voltage work with large machines, for the magnetising coils—which, it must be remembered, have to be shunt coils in self-exciting electrolytic machines—can be wound with conductors of more manageable size than would be required if they had to be energised with currents at the low-voltage of the machine. The regulation of the voltage by a rheostat is also more conveniently attained.

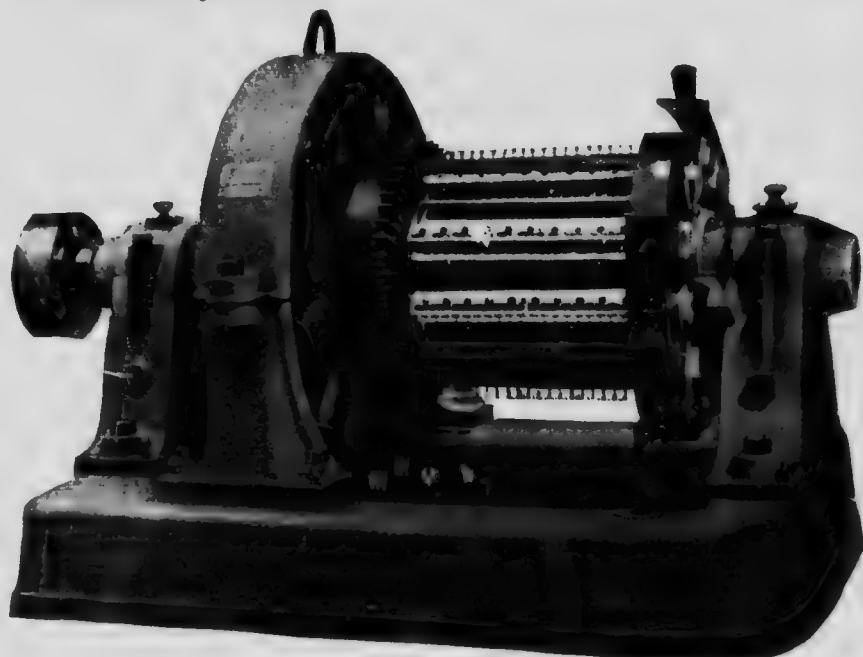


Fig. 210—Low-Voltage 45-Kilowatt Dynamo, giving 3,000 Amperes at 725 R.P.M.

The use of two commutators for the collection of heavy currents is not confined to large machines, but is employed in machines having quite a modest output. For instance Fig. 209 shows a standard machine built by the Union Electric Company, Limited, of London, for an output of 12.5 kilowatts, 2,500 amperes at 5 volts, when running at 970 R.P.M. The machine is a four-pole machine, provided with interpoles, and the two commutators are connected in parallel with the $+$ and $-$ terminals on opposite sides of the machine. Each commutator takes charge of two distinct windings with commutator segments, interleaved as previously explained (*see* page 126). The outside diameters of the armature and commutator are 12.8 in. and 9.45 in. respectively.

The brushes shown are made of a specially prepared soft metal and are arranged five in parallel on each collector bar; therefore at full load each brush should carry a current of 125 amperes, hence the necessity for using metal instead of carbon.

The machine illustrated is intended to be separately excited by the higher voltage current of the driving motor, and the terminals of the exciting current can be seen just above the main terminals. If the machine is not to be electrically driven or if the driving motor be a self-excited alternate current motor the exciting current would be taken on shunt from one of the commutators. The interpoles are excited by series currents taken from the commutators, one half the poles being excited from one commutator and the other half from the other. The bed-plate of the machine covers a floor space of 5 ft. 1 in. by 2 ft. 1½ in., and the machine is 39.6 in. high. The ample oil wells in the pedestals enable it to be run for long periods with very little attention.

As a final example of heavy-current low-voltage machines and also as illustrating, when a single commutator is used, the apparently inordinate axial length of the commutator as compared with that of the armature or field magnets, Fig. 210 depicts a 45-kilowatt machine built by the Electric and Mechanical Industrial Company of Geneva. This machine has a full load output of 3,000 amperes at from 3 to 15 volts when running at 725 R.P.M. The machine, as in some of the previous cases, is separately excited, the terminals of the field magnet circuit being clearly visible at A. There are ten magnet poles, and as the machine was built to be driven by a 500-volt motor, the exciting coils have been wound to be excited from the supply mains at a pressure of 500 volts. The brush gear and rigging are somewhat different from English and American practice, but space will not permit us to enter into details.

In connection with heavy-current machines it is interesting to note the limits that have been reached in the output of current from single commutators as compared with the size of the machine. For this purpose the number of amperes per volt forms a convenient standard of reference, but it must be remembered that for the same output this ratio will vary inversely as the square of the voltage. The highest figure given by the machines above described is 1,000 amperes per volt.

CHAPTER II

ALTERNATORS

IN Volume I. the elementary principles of alternate current working have been considered, and on pages 554 to 565 a few of the early and now historical forms of alternators have been described. More recently, partly for the reasons given in the chapter on the Electric Transmission of Power (Chapter XV., Vol. I.), the production of alternate current machinery, both single and polyphase, of all kinds developed rapidly, and such machinery now plays a very important part in electrical engineering. In this chapter it is proposed to deal, so far as space will permit, with the design and construction of modern alternate current generators or alternators, as they are briefly called.

In regard to the sizes of the machines, similar remarks to those made in the introductory paragraphs (pages 3 and 4) of the chapter on continuous current machines apply to alternators, for the same causes have operated in both cases. These causes need not therefore be recapitulated here, and we need only add that they apply more strongly in the machines now to be considered which, for reasons which will appear in the sequel, can be built more readily in large units than their continuous current competitors.

As in the case of continuous current dynamos, various methods of classification are available. The suppression of the commutator makes it possible to fix either the field magnets or the armature, and, indeed, in certain machines both these are fixed. We may therefore, in the first place, classify alternators as follows :—

- (a) Machines with fixed field magnets and rotating armatures.
- (b) Machines with fixed armatures and rotating field magnets.
- (c) Inductor machines with fixed armatures and exciting coils, but with part of the magnetic circuit revolving.

Almost without exception, modern alternators have multipolar field magnets, and therefore the number of poles does not yield a convenient basis for classification. There are, however, two chief methods of exciting the multipolar fields of modern machines which so profoundly affect the design that they may be adopted as an alternative basis of classification, and there are from this point of view the following distinct types :—

- (i.) Alternators with an exciting coil for each pole of the field magnet, or having a *multicoil excitation* :
- (ii.) Alternators with their fields excited by a single magnetising coil, or having a *monocoil excitation*.

Since the last edition of this book the rapid development of the steam turbine makes a third method of classification possible and desirable, the details of construction by which (a) slow-speed and (b) high-speed, or as

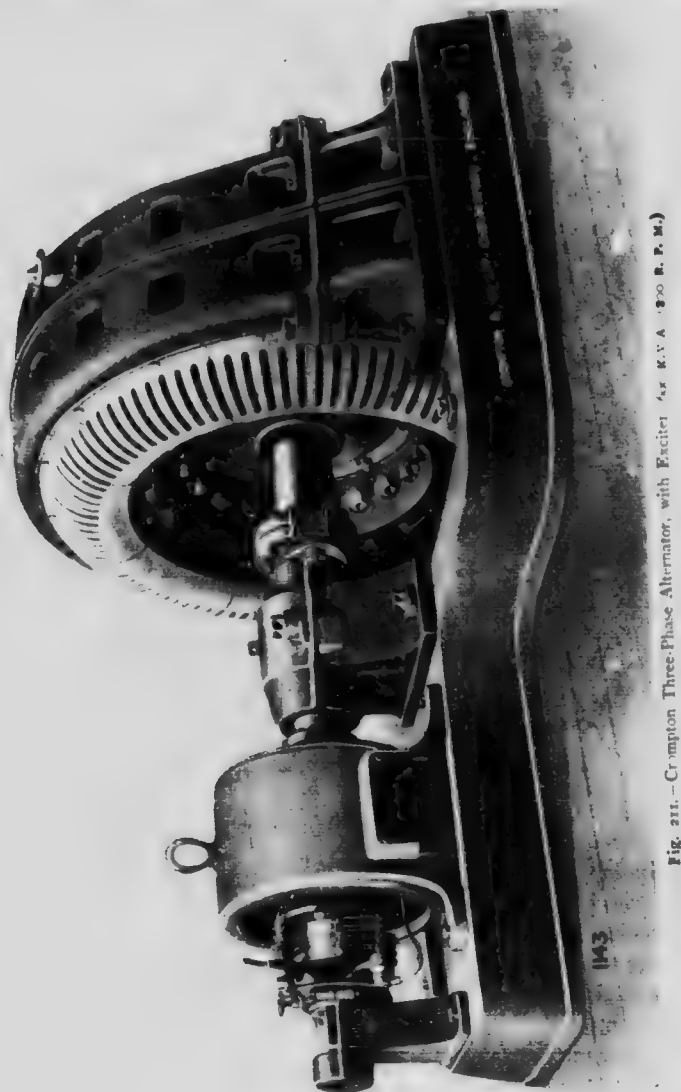


Fig. 211. — Crompton Three-Phase Alternator, with Exciter 4,800 K.V.A. 300 R.P.M.

they are called, turbo-, alternators differ from one another being quite sufficiently marked to form a good basis for classification.

For convenience, when dealing with continuous current machines, the

field-magnet part of the magnetic circuit was treated, to some extent, separately from the armature part; but with alternators it will be more advantageous to consider the whole circuit at one and the same time, though it will still be well to adopt the details of the field-magnet part as a basis for classification in accordance with the system indicated in divisions (i.) and (ii.) above.

I.—COMPLETE MACHINES

Before entering upon details, a few illustrations of complete machines will be given. The machines selected belong, almost exclusively, to the

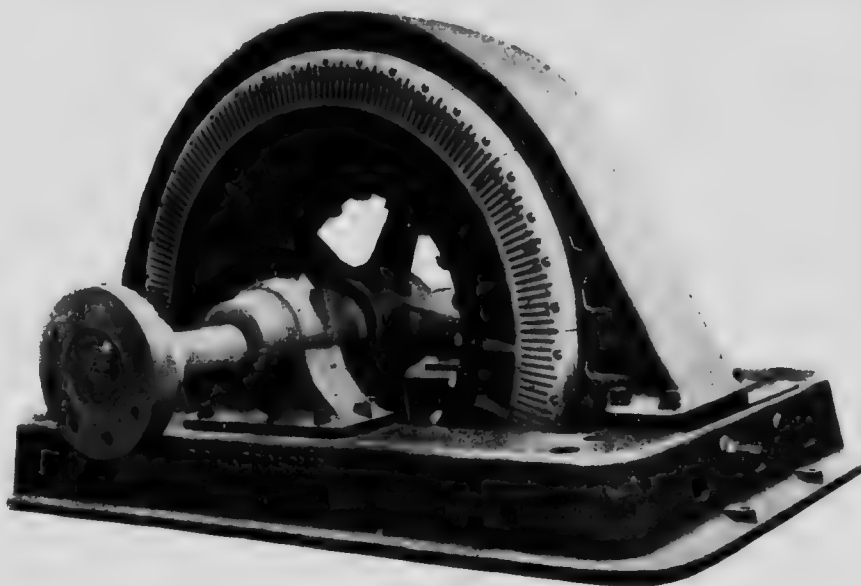


Fig. 212.—Dick, Kerr 4,000-Kilowatt Two-Phase Alternator (180 R. P. M.).

multipolar, rotating-magnet type. This method of construction is now so general that it is difficult to make a selection from the numerous examples available, and therefore no conclusions as to special excellence or otherwise must be drawn either from the inclusion or exclusion of particular machines. It will be convenient to describe "slow-speed" alternators first, and then separately "high-speed," or "turbo-," alternators. Full details of some of these machines will be given later.

Slow-Speed Alternators.—The first example (Fig. 211) is one of the standard types of alternators built by the firm of Messrs. Crompton and Co., Limited. The machine illustrated is a three-phase alternator having an output of 600 K. V. A. (kilovolt-amperes) at 2,000 volts when run at a

speed of 300 R. P. M. The continuous current exciter is carried on an extension of the bed-plate, the two shafts being coupled together and arranged for direct coupling to a high-speed engine. The machine has 20 poles, and therefore the current produced at the above speed has a periodicity of 50 ω . The rotor has a diameter of 60 inches, the core being 20 inches long, and the bed-plate measures 10 ft. 9 in. by 9 ft. 3 in.

A much larger alternator of the same general type, but having an output of 4,000 kilowatts, is shown in Fig. 212, which gives a picture of a slow-speed alternator constructed by Messrs. Dick, Kerr and Co., Limited. The machine is a two-phase, 20-pole machine, giving in each phase,

when run at 180 R. P. M., a current of 850 amperes at 2,200 volts, 30 ω , and unit power factor. The bed-plate, on which there is no arrangement for a separate exciter, is 12 ft. 7 in. wide by 20 ft. long, and the rotating field magnets carried on the rim of a five-arm flywheel have an overall diameter of 178 inches. The figure clearly shows the massive

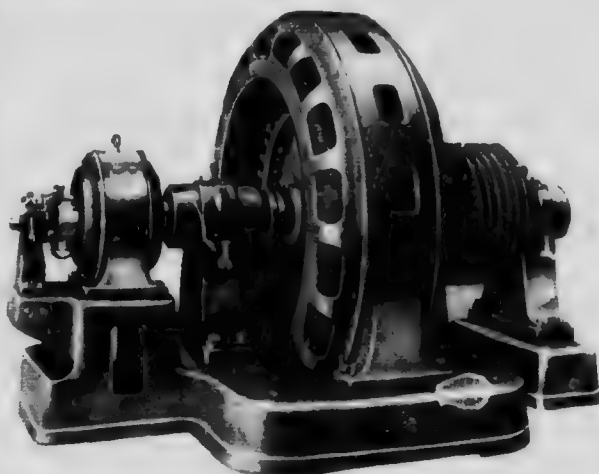


Fig. 213.—Bruce Peebles 60-Kilowatt Single-phase Alternator (480 R. P. M.).

coupling-plate by which the shaft is to be coupled to the driving engine for the transmission of the enormous power dealt with.

The next example (Fig. 213) is a rope-driven three-bearing alternator constructed by Messrs. Bruce Peebles and Co., Limited. This machine is designed for an output of 60 kilowatts (100 K. V. A.) single-phase at 240 volts and 160 ω when run at a speed of 480 R. P. M. Being a much smaller machine it differs mechanically from the machine illustrated in Fig. 211 in several respects, more particularly in the active part of the machine being axially much shorter and in its shaft being raised relatively much higher above the bed-plate. This necessitates the separate exciter being carried on a portion of the bed-plate raised sufficiently high to bring the two shafts into line. The whole arrangement is very neat for a machine with this output and speed, at which to give the high periodicity named it is necessary that there should be 40 poles.

A machine with an appearance very different from the foregoing is shown in Fig. 214. It is a 10-pole Holmes-Clayton three-phase alternator,

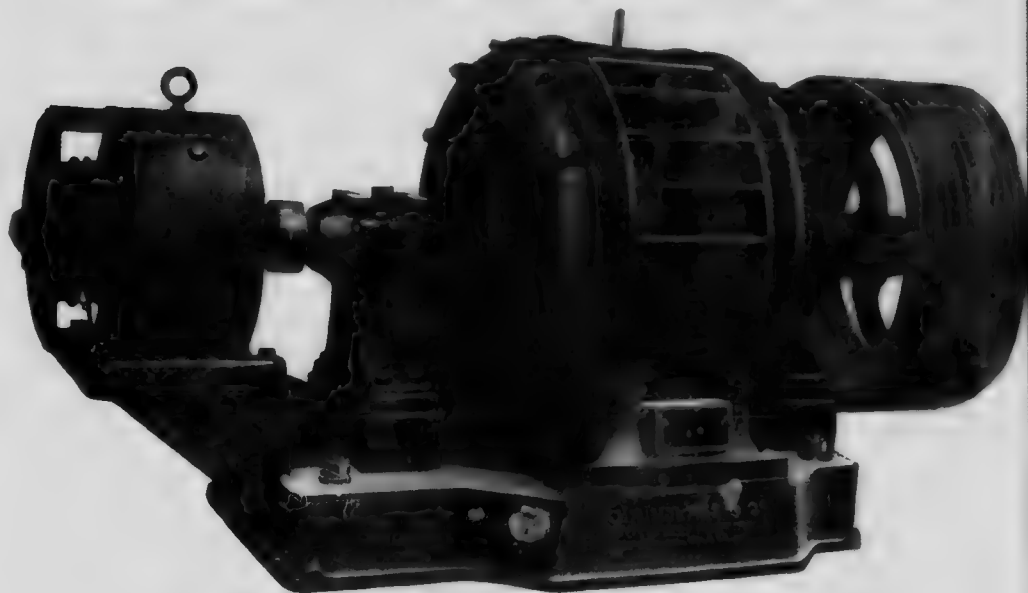


Fig. 214.—Holmes Clayton 100-Kilowatt Three-phase Alternator (600 R. P. M.).

designed and constructed by Messrs. J. H. Holmes and Co., and intended to give an output of 100 kilowatts (122 K. V. A.) at 365 volts per phase and

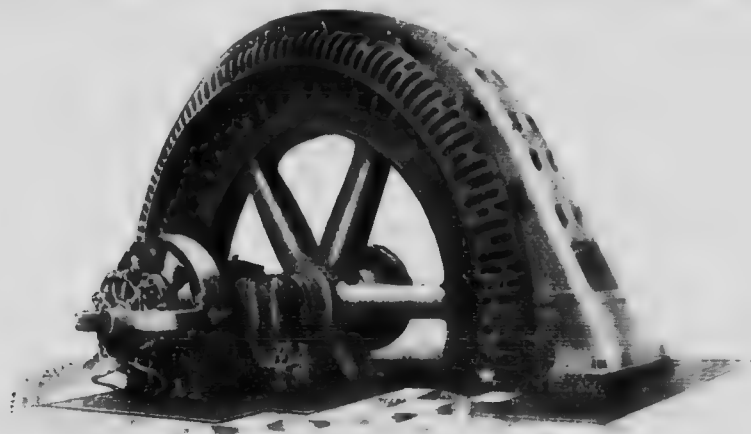


Fig. 215. Siemens 470 K.V.A. Three-phase Alternator (150 R. P. M.).

50 Ω when run at a speed of 600 R. P. M. Like the preceding machine, the height of the shaft necessitates the bed-plate being raised to clear the continuous current exciter, which in this case is carried on a supporting bracket cast in one piece with the bed-plate. Unlike the preceding machine, however, the driving pulley is on the same shaft as the

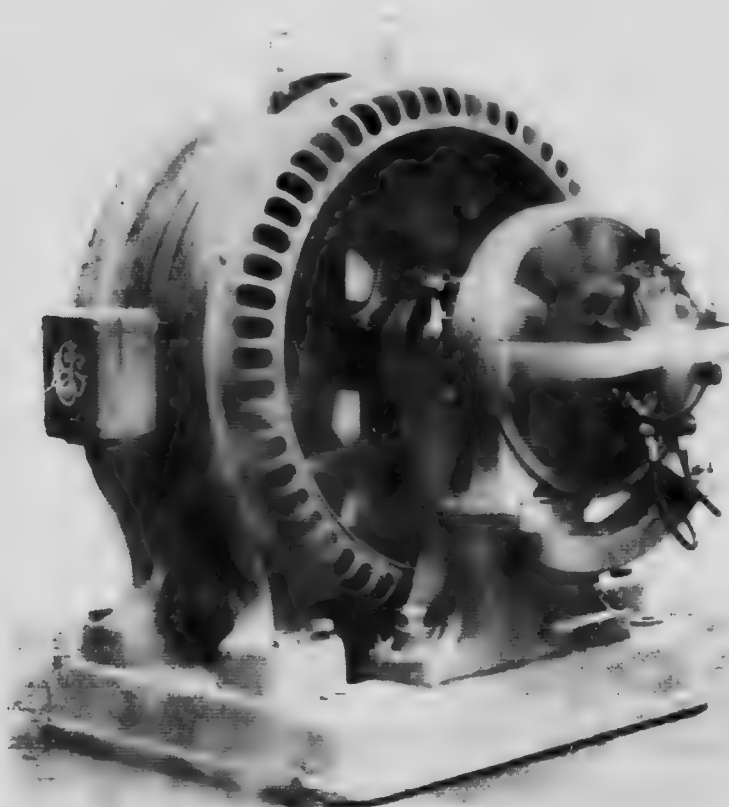


Fig. 215. 100-K.V.A. Alternator (175 R. P. M.)

machine, including the rope driving pulley occupies a height of 6 ft. 6 in. by 3 ft.

Fig. 215 is of a large three-phase generator, built by Messrs. Siemens Bros. Dynamo Works, Limited, of Stafford. It has no fewer than 48 poles carried on the massive rim of the flywheel. When run at a speed of 150 R. P. M. the current pro-

duced will therefore have a periodicity of 60 ω . The generator is designed for an output of 470 K. V. A. at 2,200 volts; it occupies a floor space of 16 ft. 8 in. by 7 ft. 4 in., the outside diameter of the stator being 13 ft. 5 in. and the inside diameter 10 ft. 6 in., and the clearance in the air gap being only 0.216 inch.

As an example of Continental design we give, in Fig. 216, an illustration of a three-phase alternator with direct coupled exciter constructed by the Electrical Company, Limited. This generator is designed for an out-



Fig. 217.—Crocker-Wheeler 32-Pole Alternator, 400-K.V.A. (225 R. P. M.)

put of 150 K. V. A. with a pressure of 3,000 volts and a periodicity of 50 cycles when running at a speed of 375 R. P. M.; it has therefore 16 poles. The 8-pole exciter is a 3 K. W. machine giving the necessary exciting current at a pressure of 110 volts. It will be noticed that the machine—which, however, is for a comparatively small output—differs from the preceding machines in being carried entirely above the surface of the bed-plate, so that the over-all height is 74 inches, the outside diameter of the revolving field magnets being 43 inches. The method of supporting the exciter should be noticed.

As an example of American design, Fig. 217 shows a machine constructed by the Crocker-Wheeler Company of New Jersey. This machine is intended for an output of 400 K. V. A. at 2,300 volts, and 60 periods per second when run at a speed of 225 R. P. M. In this case also the brackets

by which the armature casing is secured to the bed-plate are very low down, and the shaft correspondingly high, the bearings being carried by tall pedestals bolted to the bed-plate in the usual way. The machine stands 8 feet 4½ in. high, and the rotating magnets have an over-all diameter of 79½ inches.

There is one other type of slow-speed alternator which may well be referred to here, and that is the vertical-shaft type, which is frequently

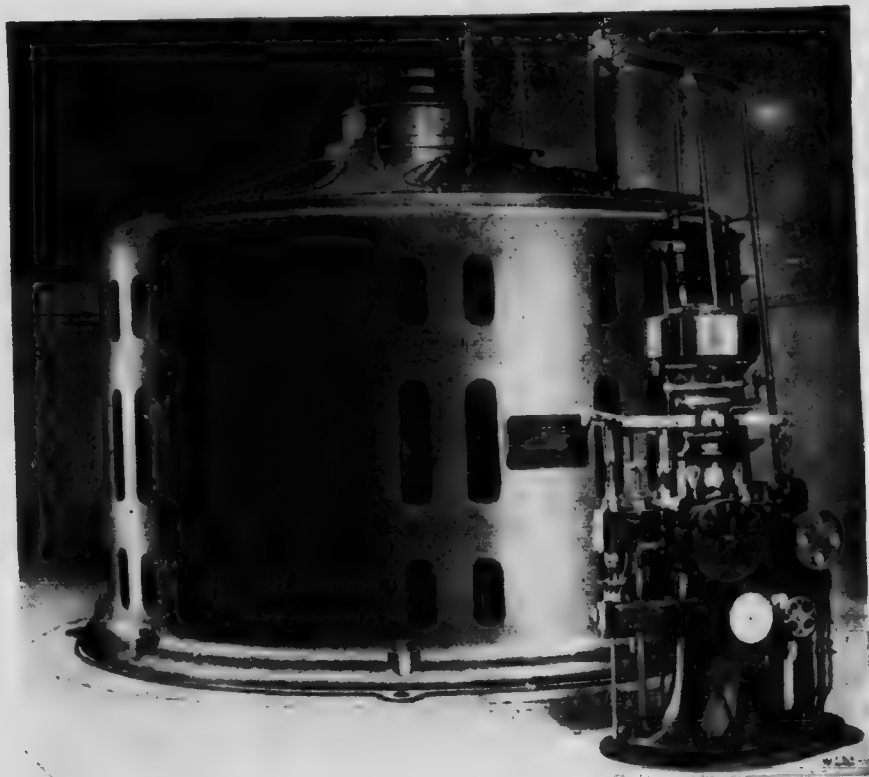


Fig. 218.—Vertical-Shaft Water-Driven Slow-Speed Alternator, 10,000 K. W. (400 R. P. M.).

used in water-power generating stations, as, for instance, at Niagara and elsewhere. The general appearance of such a machine is illustrated in Fig. 218, which depicts a 10,000 kilowatt machine of this type built by the General Electric Company of America and installed in a generating station in California. It is an 18-pole machine running at 400 R. P. M., and it generates three-phase currents at a pressure of 11,000 volts per phase and 60 $\sim$. The smaller machinery in front chiefly consists of the regulating gear for controlling the admission of water to the turbine.

Other types of slow-speed alternators not so widely used as the foregoing will be referred to later in this chapter. Those illustrated above will give the reader a good general idea of the external appearance of fairly recent and typical machines.

High-Speed Turbo-Alternators.—Illustrations of modern alternators would not be exhaustive without some reference to the high-speed turbine-driven alternators which have been so rapidly developed since the last edition of this book was published, and therefore a general description of a few of these will appropriately complete this section.

As a first example, Fig. 219 shows a complete 650-kilowatt set, including not only the alternator, but also the steam turbine driving it, as built

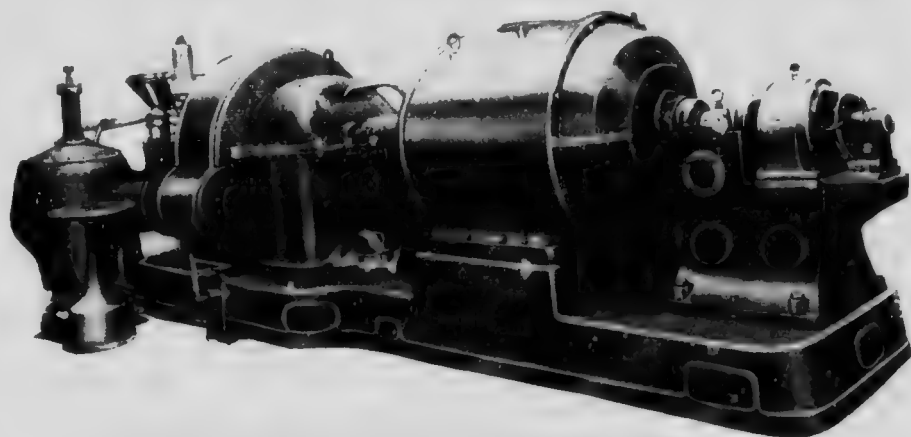


Fig. 219.—Bruce Peebles 650-Kilowatt Three-Phase Alternator running at 3,000 R. P. M.

by Messrs. Bruce Peebles and Co., of Edinburgh. The normal speed is 3,000 R. P. M., at which the set gives a three-phase current at 3,000 volts per phase with a periodicity of $50 \sim$, from which it can be inferred that the alternator has two poles only. The exciter is coupled direct to the main shaft, and is carried upon a little extension of a bracket fastened to the outside bearing at the generator end. The set, including the steam engine, has a total length of 21 feet, is 9 feet wide, and 75 inches high.

A larger set having an output of 1,000 kilowatts is shown in Fig. 220 (reproduced from *Engineering*); it is a set built by the well-known firm of Messrs. C. A. Parsons and Co., who have done so much to bring the steam turbine to its present point of efficiency. The set generates a three-phase current at 6,600 volts per phase, and $50 \sim$ when running at 1,500 R. P. M. Its total length is 33 feet, and greatest width 7 feet 4 inches. Here again the separate exciter can be seen directly coupled to the shaft of the large alternator.

The next example, Fig. 221, shows, without the driving turbine or the exciter a 1,700-K. V. A. alternator, built by Messrs. Dick, Kerr and Co., Limited¹. The machine runs at 1,500 R. P. M., covers a floor space 10 feet 8 inches long by 8 feet 4 inches wide, and stands 75 inches high from the base-plate, which itself is usually about 18 inches high. The field magnet has four poles, and the armature is wound for three-phase currents at 2,100 volts per phase and 50 ω .

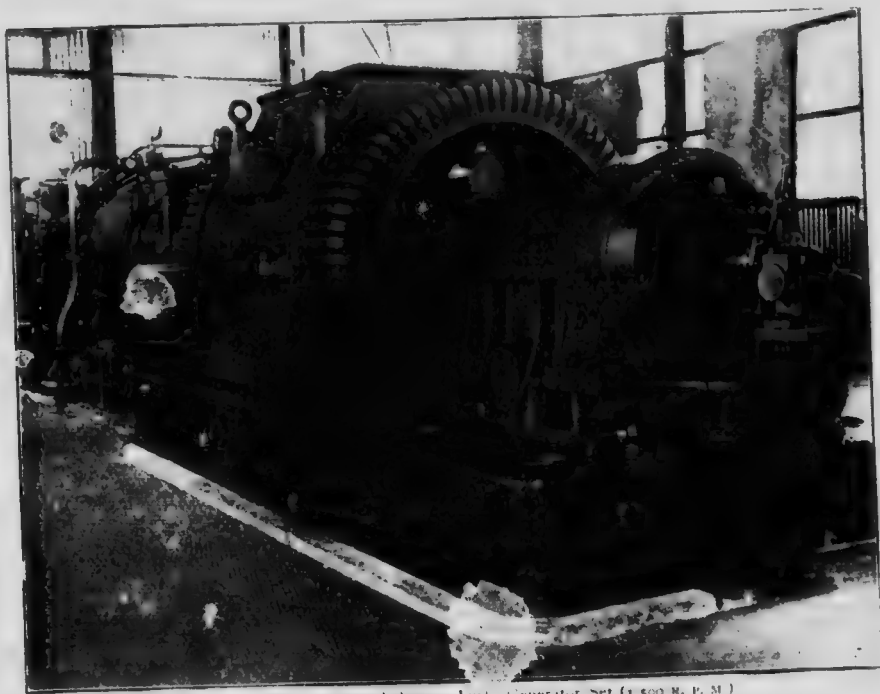


Fig. 220.—Parsons 1,000-kilowatt Turbo-Generator Set (1,500 R. P. M.)

Much larger machines constructed by this firm are referred to later (see page 452).

An interesting type of high-speed turbo-alternator which has been very widely used is the vertical-shaft alternator driven by a Curtis steam turbine and manufactured in this country by the British Thomson-Houston Company. A 3,500-kilowatt set of this type is shown in Fig. 222. It is one of two supplied in 1912 for the Tuilière generating station of the Société l'Energie Electrique du Sud-Ouest of France. The normal speed is 750 R. P. M., at which three-phase power is generated at a pressure of 5,500 volts per phase. It will be noted that the armature housing is of the closed type (see page 294). The bearing which supports the weight of the

revolving parts is supplied with oil under pressure by a three-throw Worthington pump, and a fan draws air from the outside and distributes it to the two alternators through rectangular shafts.

The last machine selected for illustration is a machine having the enormous output of 20,000 kilowatts, built by the Allgemeine Elektrizitäts Gesellschaft (the A.E.G.) of Berlin. It is shown in Fig. 223, with its turbine as it appeared in the erecting shop at the factory. The rotating field magnets of this machine weigh 50 tons, and have a peripheral speed of about 490 feet per second. In a machine of this size the actual losses, even for a highly

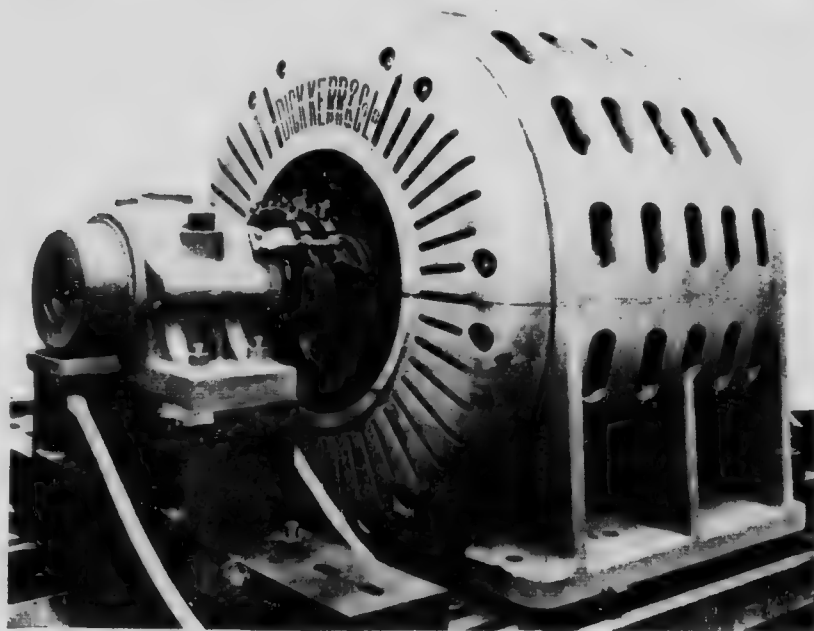


Fig. 221.—Dick, Kerr 1,600-Kilowatt Turbo-Alternator (1,500 R. P. M.).

efficient machine, mean the turning of large quantities of energy ultimately into heat in the parts of the machine, and therefore the arrangements for carrying away this waste heat have to be carefully devised. Thus so little as one per cent. of the output is 200 kilowatts or 267 H. P., and even in the friction on the bearings some hundreds of horse power are lost, making well-designed lubricating arrangements imperative.

Large as it is, however, the above machine does not represent the limit to which engineers are prepared to go in the size of single generating sets. More recently, early in 1912, the English firm of Messrs. C. H. Parsons and Co. accepted an order for a 40,000 H. P. turbine to drive an alternator

having a continuous rating of 25,000 kilowatts. The production and testing of this machine, which is to be placed in the Fisk Street generating station at Chicago, will be watched with great interest.

II. —THE MAGNETIC CIRCUIT: SLOW-SPEED MACHINES.

As explained on page 222, the whole magnetic circuit will be dealt with in the same section, instead of, as in the case with continuous current machines, the field magnets and the armature being taken in separate sections. For this purpose the classification followed will be the second classification given on page 220.

Multicoil Fields.—

These fields—in which, as a rule, there is an exciting coil on the core behind each pole face—may have either (a) fixed field magnets or (b) rotating field magnets. The third division (c) of page 220 does not apply in modern machines, though some of the earliest inductor machines were of this type (see pages 272 and 273).

(a) *Fixed Field Magnets.*—This type of alternator is not frequently met with in machines of recent construction, but when it is the multicoil fixed magnets—especially in polyphase machines—do not differ greatly, except in the shape of the pole faces or shoes, from the corresponding magnets used for continuous current generators.

Thus Fig. 224, which represents the carcass of the field magnet of a 180-kilowatt two-phase alternator built by the British Westinghouse Electric Company, does not differ, except in the proportion of the parts, very much from Fig. 13, belonging to one of the same company's multipolar continuous current generators. The chief differences are that in the alternator the poles are more numerous and more closely placed, and that they

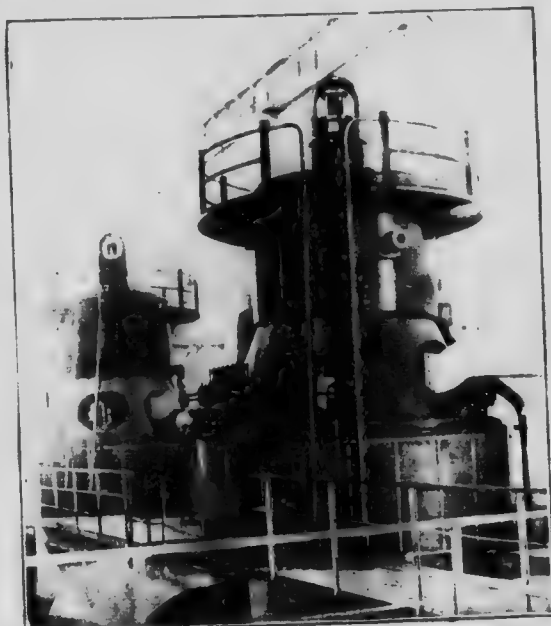


Fig. 222.—2,000-Kilowatt R.T.H. Vertical-Shaft Turbo-Alternator, driven by Curtis Turbine. (750 R. P. M.)

are narrower in proportion to their axial length. It is interesting to note that whereas the total height of the 180-kilowatt alternator is $71\frac{1}{4}$ inches, that of the 200-kilowatt continuous current machine is $77\frac{1}{4}$ inches, whilst the heights of the axes of the shafts in the two cases are 35 and $38\frac{1}{2}$ inches respectively. For the same output, therefore, the difference in size of these two machines for producing electrical power is not very great.

A complete multicoil magnet machine with fixed field magnets, as made by the same company, is shown in Fig. 225. The magnet cores—of which



FIG. 225.—A.E.G. 80,000-Kilowatt Turbo-Alternator.

there are eighteen—project, as usual, from an encircling yoke, and each one carries a substantial magnetising coil. The pole faces are rectangular, and occupy a considerable fraction of the periphery. Except for the absence of the commutator the armature is very similar in appearance to the armature of a multipolar continuous current machine. Magnetically, the similarity is very close, for it is built up of toothed discs and driven by a spider keyed on to the shaft. In fact, except for the shape of the pole pieces, the two magnetic circuits are identical.

The machine illustrated is wound to give an output of 375 kilowatts with two-phase currents at 60 periods per second, the speed of rotation

being 400 R. P. M. The yoke ring is about 112 inches in diameter, and the centre of the shaft is 54 inches from the floor, the lower part of the yoke ring being cast with the bed-plate. The over-all length parallel to the shaft is 150 inches, of which 50 inches is occupied by the pulley face



Fig. 224.—Carcass of Multicoll Fixed Field Magnet of Alternator.

The exciting current at full load is 55 amperes at 125 volts, or 6.87 kilowatts, which is 1.8 per cent. of the maximum output.

"Copper"-Type Alternators.—The forms of multicoll fixed field magnets, diverse from anything found in modern continuous current practice, were, at one time, numerous and important. A very widely used type has already been described in the historical section in the Siemens (Fig. 535, Vol. I.) and also in the Ferranti (Fig. 537) alternators. It consists of a double

crown of poles facing one another at opposite sides of a narrow gap in which discoidal armature coils revolve. The poles are alternately *N* and *S*, a north pole on one side facing a south pole on the other.

The field magnets of a much more recent Ferranti machine of this, the "copper," type are shown in Fig. 226, in which will be observed the double crown of magnets facing one another with a narrow gap between them. The core of each magnet projects from a massive yoke ring, through

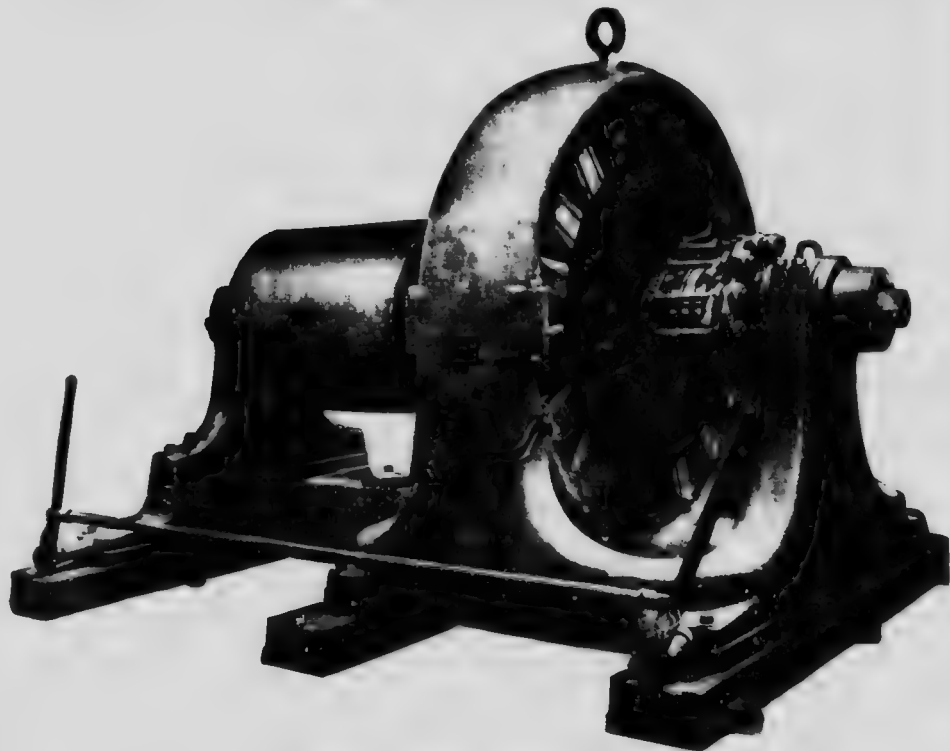


Fig. 225.—Westinghouse Multicoil Alternator with Fixed Field Magnet.

which it passes, the ends of the cores being visible on the outside of the ring. There are two such rings, each carrying a circular "crown" of 40 electro-magnets at right angles to the plane of the ring, the latter being built up of four parts bolted together. The two rings are rigidly held at the required distance apart by the supporting brackets and by the insertion at intervals of distance pieces, the positions of which can be seen in the figure. The field magnets illustrated are for a machine designed to give an output of 650 kilowatts at 11,000 volts. As there are 40 electro-magnets in each yoke ring placed with their poles of opposite polarity

facing one another, there will be 40 changes in the direction of the E. M. F. during each revolution of the armature, thus giving 20 complete cycles per revolution. The armature runs at 250 R. P. M., and the periodicity is therefore 5,000 periods per minute, or, in the usual units, 83 periods per

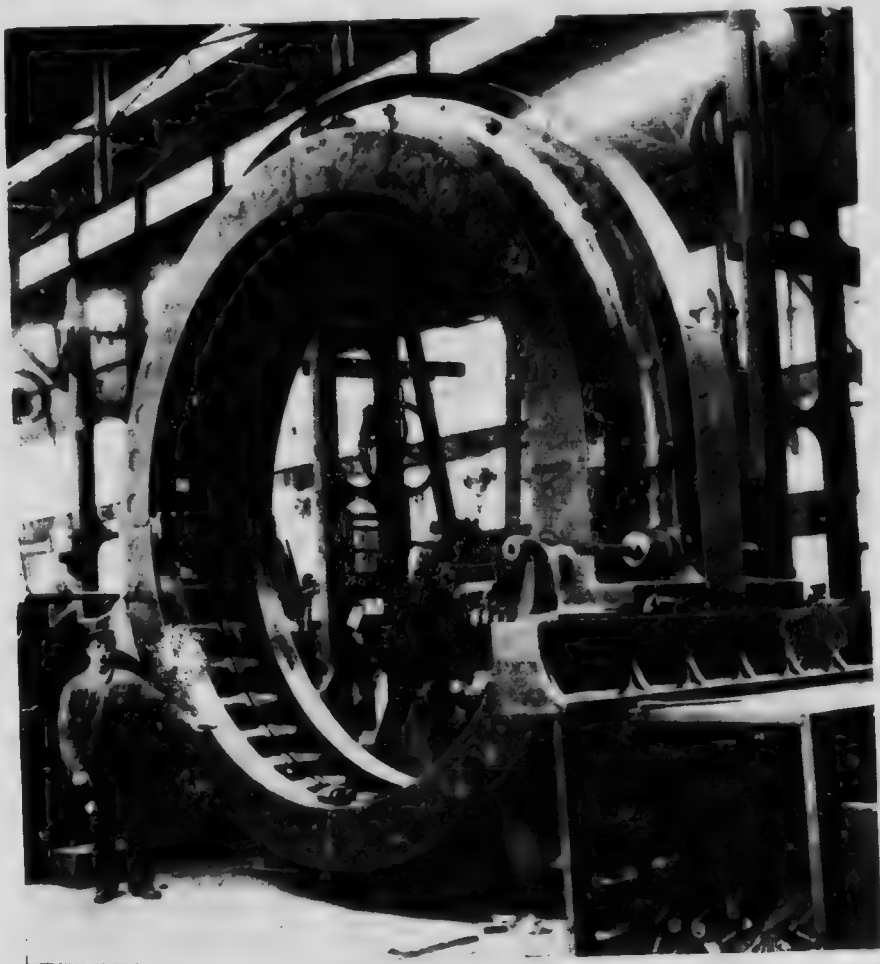


Fig. 226.—Field Magnet of Ferranti "Copper" Type Alternator.

second, which is higher than what is now the most usual practice. The electro-magnets are wound with copper strip on edge, in the manner illustrated in Fig. 23, and the windings are held in position by the pole faces, which are fixed to the body by countersunk screws. The over-all diameter of the yoke rings is 183 inches.

The armature coils which are to revolve in the gap between the double crown of electro-magnets are shown in Fig. 227, which represents the armature of a 500-kilowatt alternator supplied by Messrs. Ferranti, Limited, to the Hampstead Central Station. It will be noticed first that the coils are mounted on the outside of the rim of an ordinary engine flywheel, so that this flywheel being designed with reference to the engines to give the required steadiness of running, no additional flywheel need be mounted on the shaft, as is necessary in some other designs of



Fig. 227. - Armature of Ferranti "Copper" Type Alternator.

alternators and some of the large continuous current machines. The coils are carried by steel bolts, fixed in cored holes of elliptical section in the outer periphery of the rim. Each hole contains an elliptical cast-iron nut drilled and tapped to receive the steel bolt; these nuts are about $\frac{1}{4}$ inch smaller all round than the holes in which they are placed, the remaining space being filled up with a composition of melted sulphur, which, on hardening, forms a firm mechanical support for the nuts, and, in addition, efficiently insulates them and the bolts from the metal of the rim. The bolts are in pairs in the same radial plane, and each pair of bolts carries a pair of coils, one on either side of that plane. The inner ends of the two coils carried by one pair of bolts are electrically connected, so that each pair of coils with its bolts forms a separate unit of the armature, which is electrically joined to the units on either side by means of the lugs, which can be seen projecting inwards in the figure.

The armature illustrated is designed to give an output of 500 kilowatts

at 2,100 volts when run at a speed of 270 R. P. M. There are 40 coils in all, and the field in which they revolve is therefore precisely similar to the field represented in Fig. 226; the speed, however, being higher, the periodicity is 90 $\sim$ instead of 83 as in the former case. The diameter of the flywheel is 100 inches, and the over-all diameter of the armature coils 148 inches.

A complete machine of this type, together with its Ferranti driving

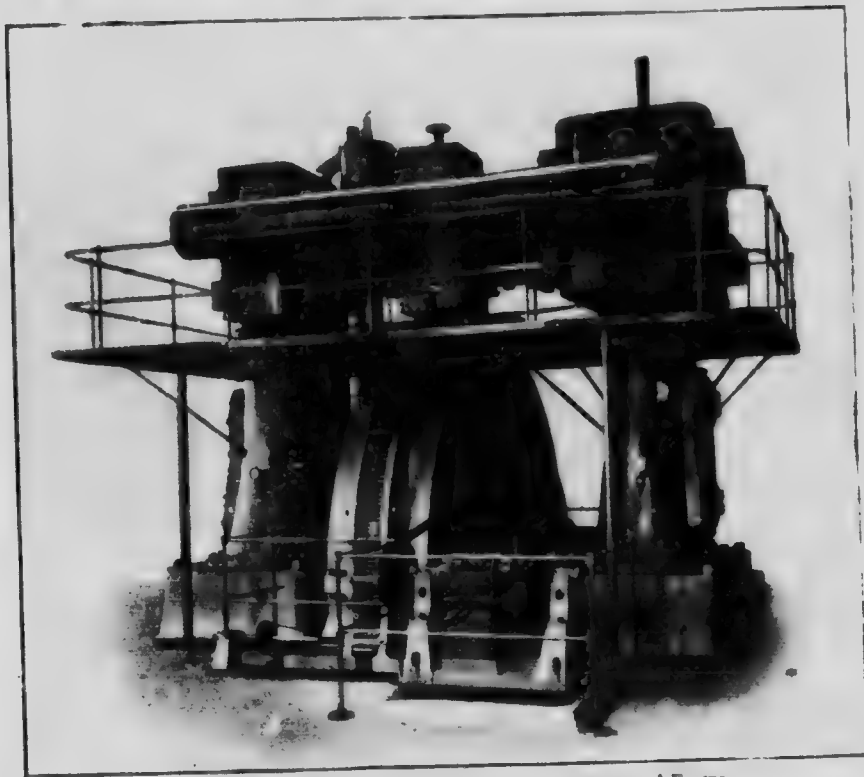


Fig. 228.—Ferranti 600-Kilowatt "Copper"-Type Alternator and Engine.

engine and continuous current exciter, as supplied to the Derby Corporation, is shown in Fig. 228. The output of the set is 600 kilowatts at 2,100 volts when running at 214 R. P. M. There are, in this case, 28 coils on the armature and the same number of pairs of electro-magnets on the yoke rings, the frequency of the single-phase currents produced being 50 $\sim$. The largest machine of this type hitherto built was supplied to the City of London Electric Lighting Company, Limited, and had an output of 1,500 kilowatts when running at 150 R. P. M.; its over-all diameter was 23 feet

In regard to voltage, these alternators have been built to give 10,500 to 11,000 volts on a working load, and 12,000 volts on test.

Machines with copper-type disc armatures and fixed field magnets with multicoil excitation, but smaller than those described above, were at one time manufactured by Messrs. Crompton and Co., Limited. They have, however, been superseded by machines of the revolving magnet type with multicoil excitation. Those interested in the history of the subject will find other copper-type machines fully illustrated and described in the last edition of this book.

Pole-Armature Type.—This type of machine has the armature coils wound upon cores which project radially outward from a revolving hub or a flywheel rim. In the early days the type was taken up by more than one inventor, and good machines originally designed by Drs. J. and E. Hopkinson, and manufactured by Messrs. Mather and Platt, Limited, played at one time an important part in the development of the subject. Full descriptions of the various modifications of the type will be found in the earlier editions of this book, but it also has been displaced by the revolving-field types described later in this chapter. One great disadvantage of the type was that it could generate single-phase currents only.

(b) *Rotating Field Magnets.*—When we pass to multicoil rotating field magnets we meet with many patterns which differ considerably from anything used for continuous currents. Such field magnets were used in one of the historical machines already described (see Fig. 534, Vol. I.), and played an important part in the early development of alternators. Other forms have been described in the earlier editions of this book. Perhaps the greatest advantage gained by fixing the armature and causing the field magnets to rotate is that no sliding contacts are required for the high-voltage currents which are usually produced by modern alternators. Whenever such contacts are required they have to be carefully designed, because of the difficulties of effective insulation under the conditions of working. With the field magnets rotating, the only sliding contacts required are the ones for introducing the magnetising current; the machines being separately excited, this current is usually of low voltage, and the design of the slip rings is therefore quite simple.

The above remarks apply to machines of this type, whatever may be the speed at which they are designed to run. It has, however, already been remarked that the excessively high speeds at which steam turbine-driven alternators are run introduce problems which are either absent from, or are unimportant and negligible in, slower-running machines. It will therefore be convenient in what follows to treat the two classes of machines separately.

(b₁) *Slow-Speed Machines.*—As already remarked, the whole tendency of modern development is in the direction of building larger and larger units,

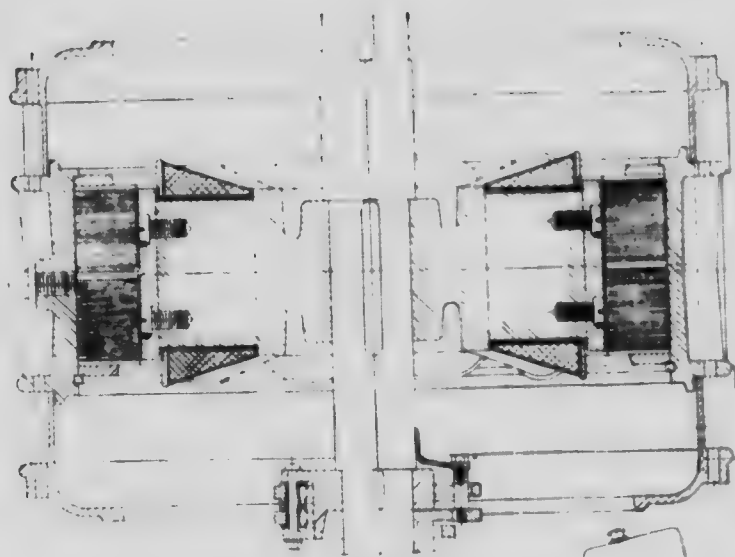


Fig. 231.

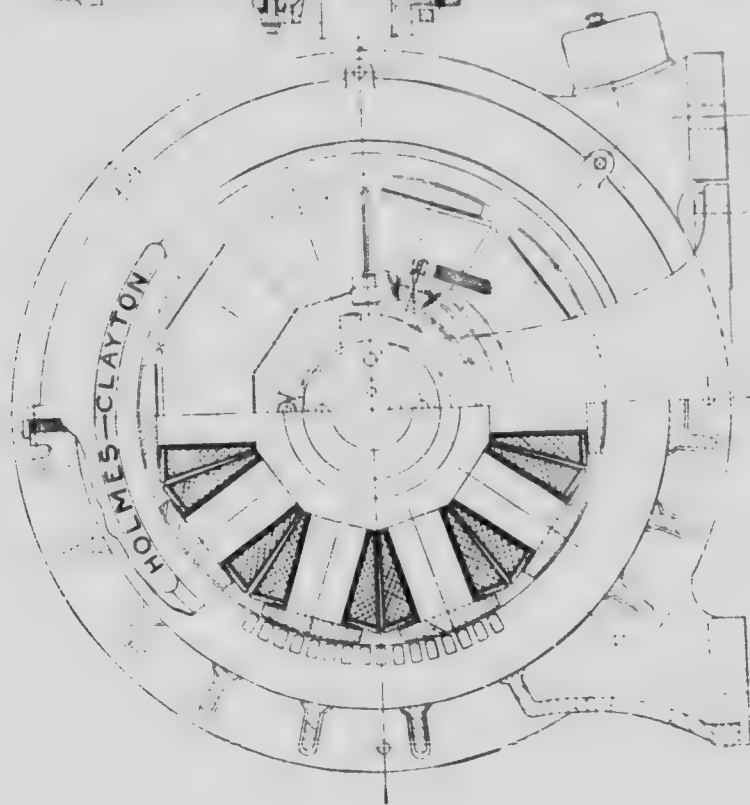


Fig. 232.

Holmes-Clayton Alternator 40 K. V.

and therefore most of our illustrations will be drawn from such machines. It will, however, be instructive to commence with quite a small machine, and for this purpose we have selected an alternator constructed by Messrs. J. H. Holmes and Co., similar to, but smaller than, the alternator shown in Fig. 214.

The machine, which is designed to give a three-phase output of 40 K. V. A. at 200 volts between lines when running at 600 R. P. M., is shown in cross-section in Figs. 229 and 230. It has ten poles, and therefore gives a current with 50 periods per second. The field-magnet cores, as will be seen in Fig. 230, are cast solid with the hub, but are provided with separate pole shoes, which are screwed on to the ends of the cores. The over-all diameter of the rotor is 20 in., and the cores are 4.25 in. long, with a cross-section 6.4 in. by 2.45 in. The whole of the interpolar space (Fig. 229) is occupied by the field coils, which are wound to a wedge-shape section so as to utilise this space to the best advantage. These coils are held in their places against the effects of centrifugal force by the pole shoes. Details of the slip rings from which the current is led into the coils can be made out in Fig. 230, and details of the brushes and brush holders can be seen in Fig. 229.

The air gap is $\frac{1}{8}$ in. opposite the pole shoes, and therefore the diameter of the armature face is 20.25 in. The armature is 7.5 in. long measured parallel to the shaft, and is made up of the usual stampings with one ventilating duct in the middle; these stampings have a radial depth of 2.7 in., and are clamped in position in the housing by end plates. The slots are rectangular in section, with only a very narrow opening on the face of the armature; there are altogether 90 slots, which gives nine slots per pole or three slots per pole per phase. The full load current is 115 amperes per phase, which at unit power factor, and with a perfectly balanced load, gives an output of 40 kilowatts.

In large machines of this type in which the poles are usually very numerous, the yoke of the field magnet part of the magnetic circuit is formed by successive portions of the rim of a flywheel, on which, as a rule, the magnet cores are bolted. It must be remembered that the polar projections are alternately of opposite polarities, and therefore the machine consists magnetically of a great number of magnetic circuits (compare Figs. 38 and 39) arranged round this rim; the actual length of any particular line in the rim cannot much exceed twice the pole pitch. The general form of the cross-section of this portion of the path can be fairly well seen in some of the preceding figures (see Figs. 211 to 218), but fuller details will be given later.

Attention may also be called to what by analogy, but to a very limited extent, may be regarded as the yoke of the armature part of the magnetic circuit. These armatures, as a rule, consist of a frame ring or housing,

often cast in two parts, or in very large machines in four parts for convenience in handling, in a similar manner to the yoke rings of the field magnets of multipolar continuous current dynamos. One of these frames is shown in Fig. 231, in this case cast in two halves, the lower half being provided with feet or brackets for bolting to the bed-plate or foundation. The laminated iron of the armature is then built up inside the cast ring in

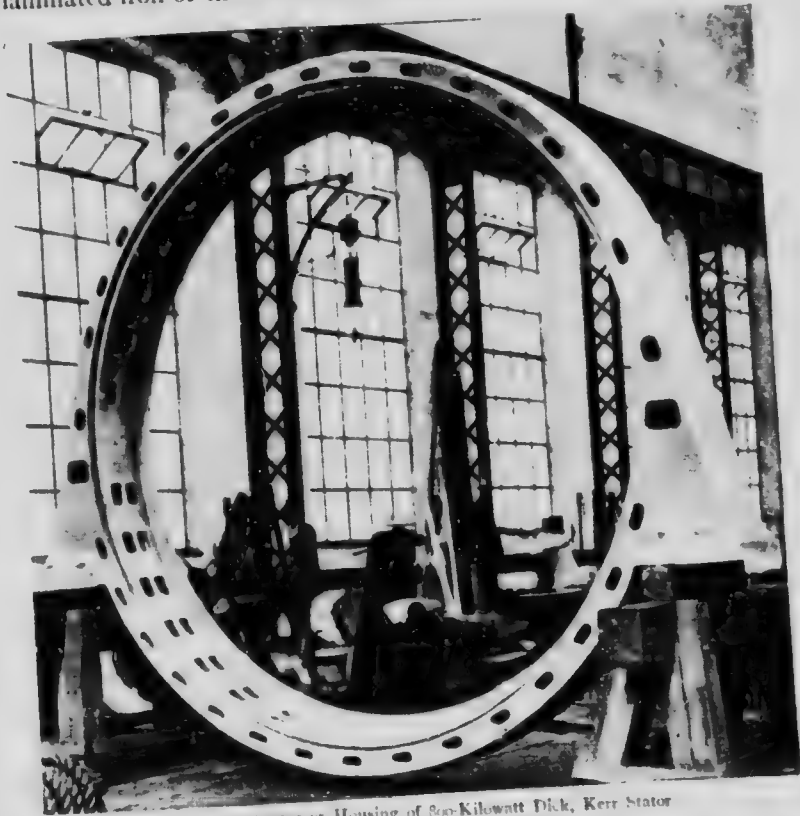


Fig. 231. Frame or Housing of 800-Kilowatt Dick, Kerr Stator

the manner shown in Fig. 232, which represents the two halves of the unwound armature of a machine made by Messrs. Dick, Kerr and Co., who are also the makers of the frame or housing shown in Fig. 231. Other views of the stator, of which Fig. 231 is the frame, are given subsequently in Fig. 233, where details of the size will be found. The armature in Fig. 232 was afterwards wound for an output of 500 kilowatts, two-phase at 10,000 volts and 60 $\sim$, the rotor having 52 poles and running at 200 R. P. M. The shape of the external castings in these cases may be compared with the different forms which are clearly shown in Figs. 211 to 222.

The magnetic circuit of this type of alternator is well shown in Figs. 233 and 234, prepared from drawings kindly supplied by Messrs. Mather and Platt, Limited. Fig. 233 is a drawing, partly in section, at right angles to the shaft, showing two poles of the field magnet and the corresponding portion of the armature iron and ring frame, whilst Fig. 234 shows a radial section parallel to the shaft, through one of the magnet poles and the armature and frame. In each drawing the exciting coils are shown on the magnet poles.

It will be noticed that each magnet core is bolted on to the rim of the flywheel by two substantial bolts, which pass a fair distance into the cores, and that additional stiffness is secured by the depth to which the cores are sunk into the rim. The pole faces at the ends of the cores are brought



Fig. 233.—Unmounted Stator for 500-Kilowatt Dick, Kerr Alternator.

close up to the armature core iron, which is laminated in the same manner as in the armature cores of continuous current machines, and for the same reasons (see page 400, Vol. I.)

The cast-iron frame appears to be in two halves, with a kind of mitre joint between them, and bolted together by the bolts A and B (see both figures), thus enabling the laminated core discs D to be built up in much the same way as previously described for continuous current machines. In this instance, the slots in which the conductors are to be placed are completely closed by a thin partition of iron at the end next to the pole faces, and therefore the armature belongs to the "tunnel" type. The mean path of the lines of magnetic flux is shown by the dotted lines; in actual practice very little of the flux passes through a slot, the greater portion being confined to the soft laminated iron, as already explained.

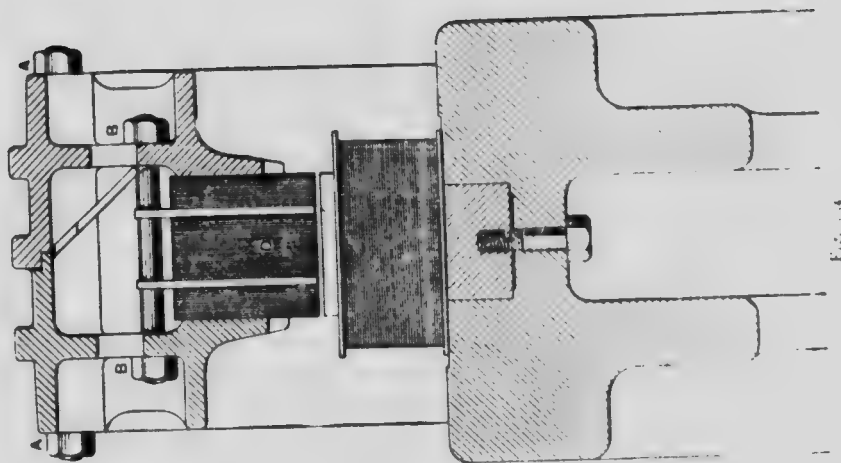


Fig. 4

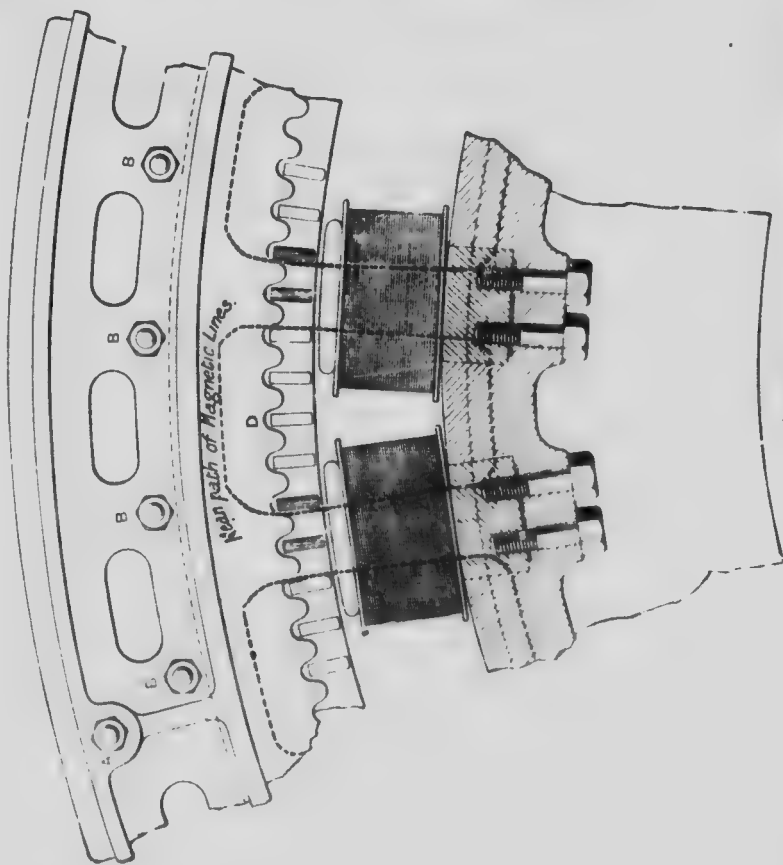


Fig. 5
Magnetic Circuit of Motor of Fig. 4

It must, of course, be understood that very little, if any, of the changing flux in the laminated core iron actually finds its way into the encircling frame, the chief function of which is to give the necessary mechanical support and stiffness to the laminated iron which is intended to carry this flux. If the magnetic lines found their way in any appreciable quantity into the solid iron, their rapid changes of position would give rise to eddy currents, which would lead to a waste of energy and to heating, with a consequent lowering of the efficiency of the machine.

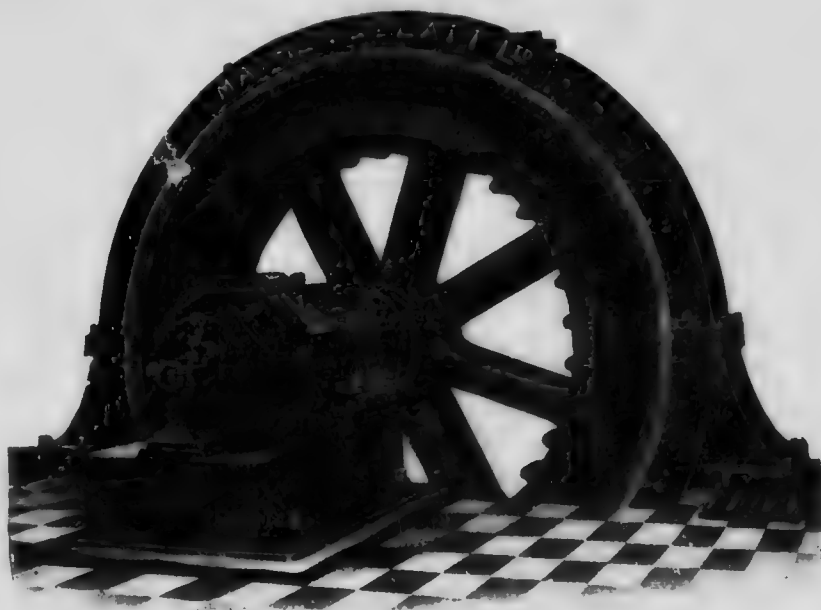


Fig. 235.—Mather and Platt Multicoil Rotating-Field Alternator, 500 Kilowatts.

The actual machine to which the above drawings refer is shown in Fig. 235, which represents a somewhat old type of three-phase alternator and exciter built by Messrs. Mather and Platt to give an output of 500 kilowatts at 120 R. P. M. The armature may be wound for any one of five different standard pressures varying from 6,500 to 300 volts, the frequency being 40 ω . The whole machine weighs 30 tons, and the over-all diameter of the revolving field magnets is 186 inches. The efficiency at full load is 93 per cent. The whole of the armature and frame can be moved parallel to the axis and relatively to the field magnets, thus readily allowing the windings of either to be inspected. The flywheel upon which the field magnets are built up is of sufficient mass to ensure

steady running under varied conditions of load, and in parallel with other machines.

The building up of the rotor wheel and the design of the pole cores, and their method of attachment to the wheel, are naturally details to which much consideration has been given, and it is interesting to note some of the solutions of the problems involved which have been adopted in practice.

Dealing first with machines of comparatively small output, the wheel itself often takes a disc shape to which the rim for carrying the cores is secured in various ways, some of which will appear in subsequent illustrations. The disc is frequently pierced with holes both to secure lightness and also for ventilating purposes.

For the larger machines a fly-wheel with the usual spokes and rim is either cast in one piece or carefully built up so as to avoid undue strains in the material and to



Fig. 236.—Crocker-Wheeler Rotor, partly assembled.

secure greater freedom from breakdown. It must not be forgotten that, unlike a simple flywheel, the rim of a flywheel alternator has, in addition to centrifugal forces, to sustain very large tangential forces due to the transformations of energy taking place at its periphery.

The first example, given in Fig. 236, shows the rotor not quite complete of a Crocker-Wheeler alternator. In this case the hub, the six spokes, the rim, and the magnet cores are one solid steel casting. The rotor, which is 62½ inches in diameter and carries 28 pole shoes, is for a machine having an output of 150 kilowatts at 257 R. P. M. For larger machines the pole shoe and core are in one solid piece bolted to the rim, which is

may be turned cast solid with the hub and spokes. A completed machine of this type is depicted on page 226.

The next example, in Fig. 237, shows the completed rotor of a 500-

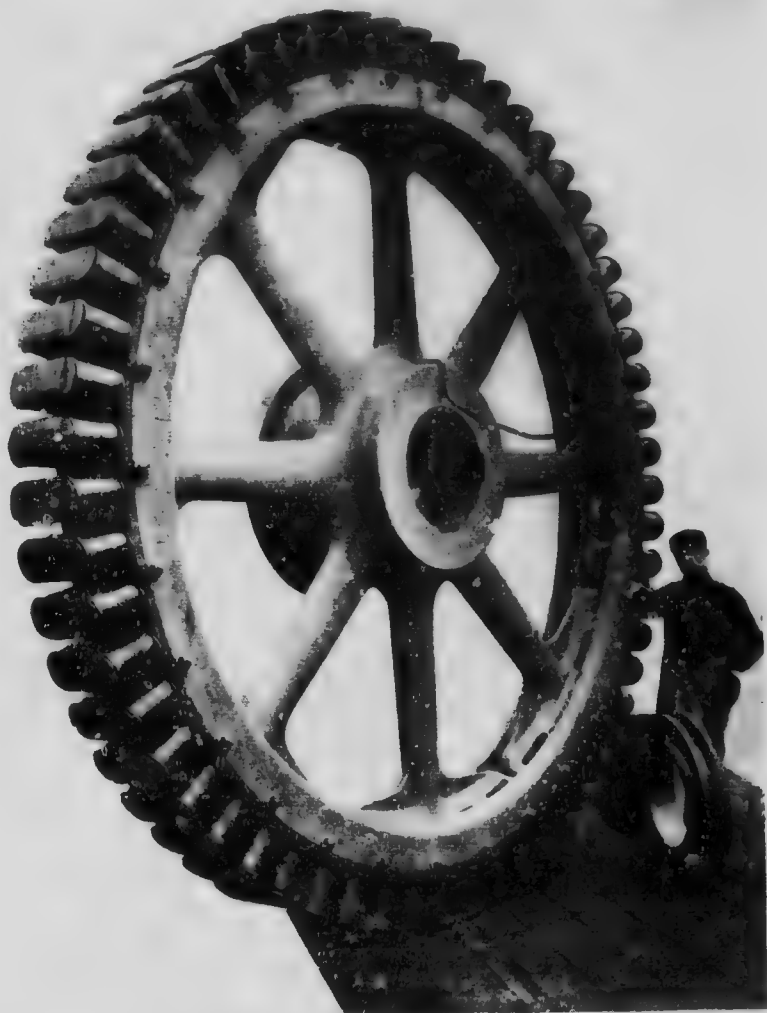


Fig. 237. Rotor of a 500 Kilowatt Dick, Kerr Alternator.

kilowatt alternator built by Messrs. Dick, Kerr and Co., Limited. In this case it is important to notice that the eight spokes, which are cast solid with the hub, carry in their outer ends the eight sections of a discontinuous

rim to which continuous rings for carrying the magnet cores are securely bolted; details of these rings will be given later. The external diameter of the rotor is 12 feet; it carries 60 poles, and is designed for a speed of 80 R. P. M., giving a periodicity of 40 $\sim$.

In Fig. 238 still another method of construction is indicated. The rotor

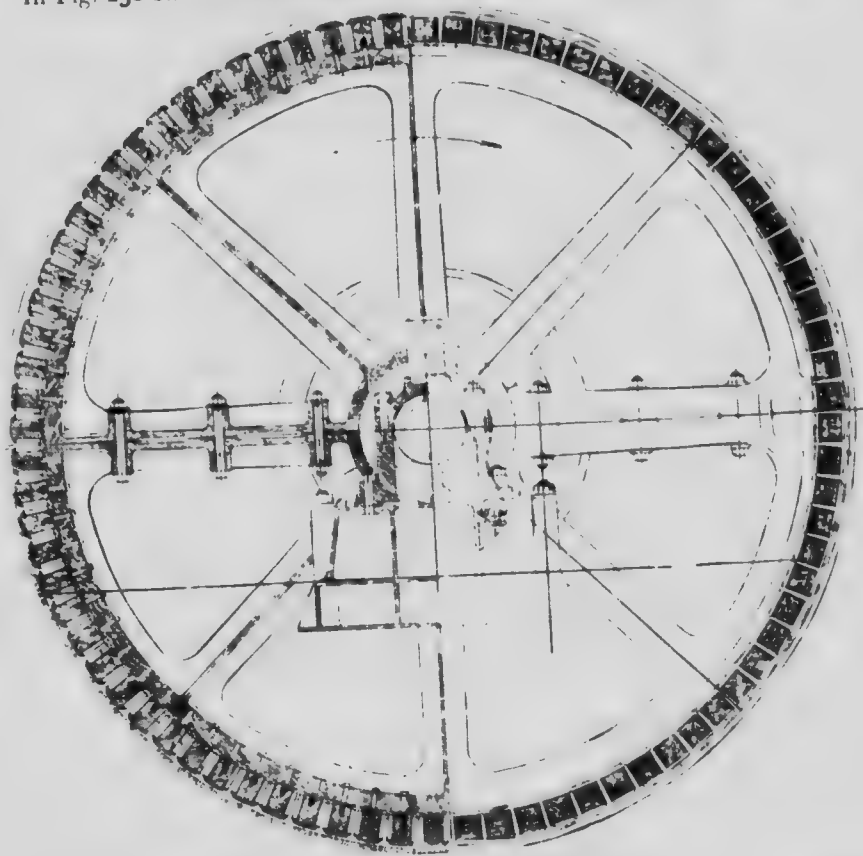


Fig. 238.—Rotor of Brush Alternator, 1,000 Kilowatts, 75 R. P. M.

shown, which has an external diameter of 203.5 inches (16 ft. 11.5 in.), belongs to an 80-pole machine with an output of 1,000 kilowatts at 75 R. P. M., built by the Brush Electrical Engineering Company. It has eight spokes, six of which are simple and the other two compound. The wheel has been cast in two halves, and in each half three spokes and two half-spokes have been cast solid with the rim, and the half-spokes afterwards bolted together to form the complete wheel. The inward ends of the spokes, however, do not form a continuous solid hub or half-hub, but when the half-spokes

are bolted together the hub is in eight separate pieces. This can be more clearly seen in Fig. 239, which gives a picture of the completed rotor supported by, but not finally secured to, its shaft. The dividing of the hub, as does the dividing of the rim in other methods of construction, enables the

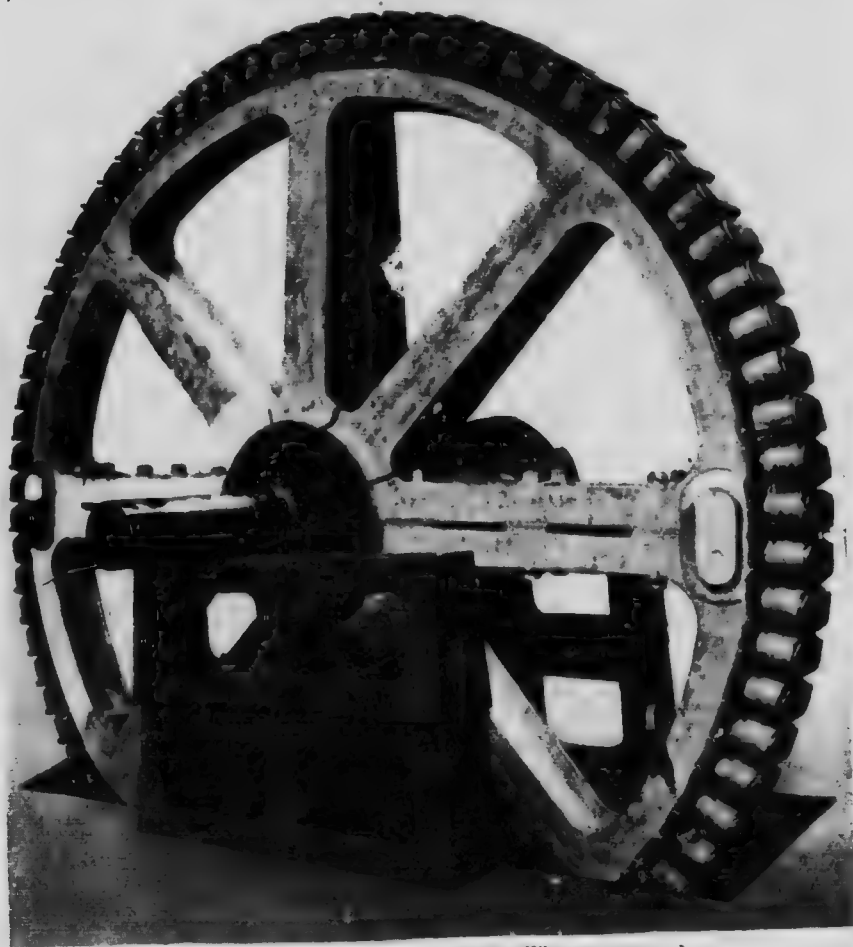


FIG. 240.—Rotor of Brush Alternator (1,000 Kilowatts, 75 R.P.M.).

massive castings to cool down from the molten state with a minimum of internal strain, which might develop to a dangerous extent if the whole hub, spokes, and rim were cast in one solid piece. How the split hub of this particular rotor is mechanically connected to the shaft so as to secure a satisfactory drive from the shaft to the rotor can be seen from Fig. 240,

PLATE V

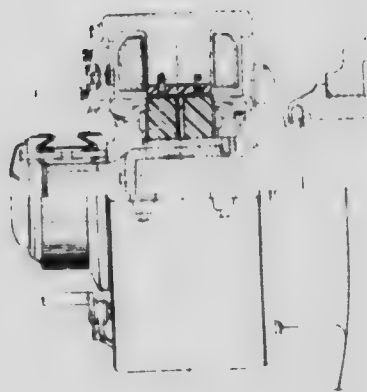
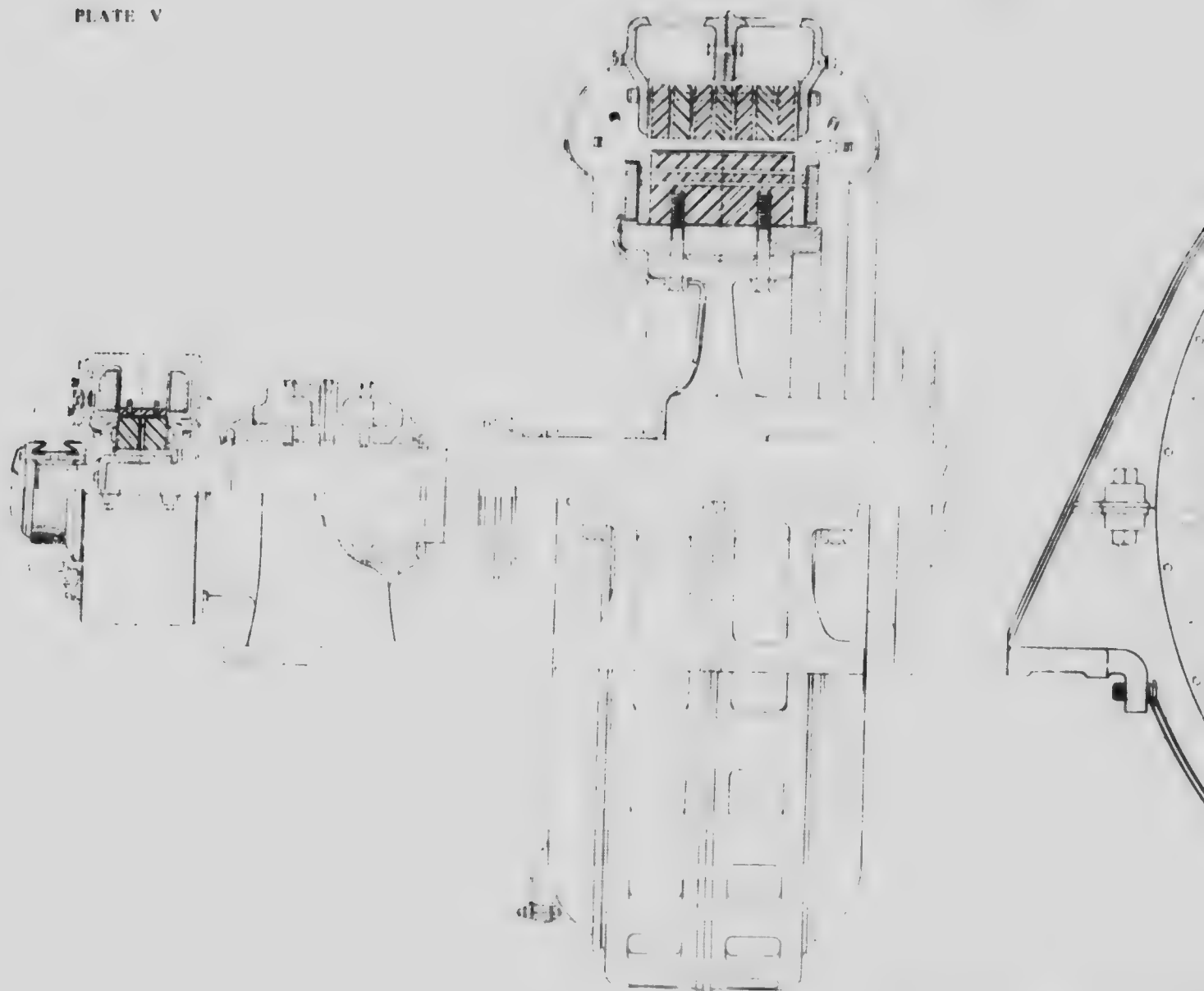
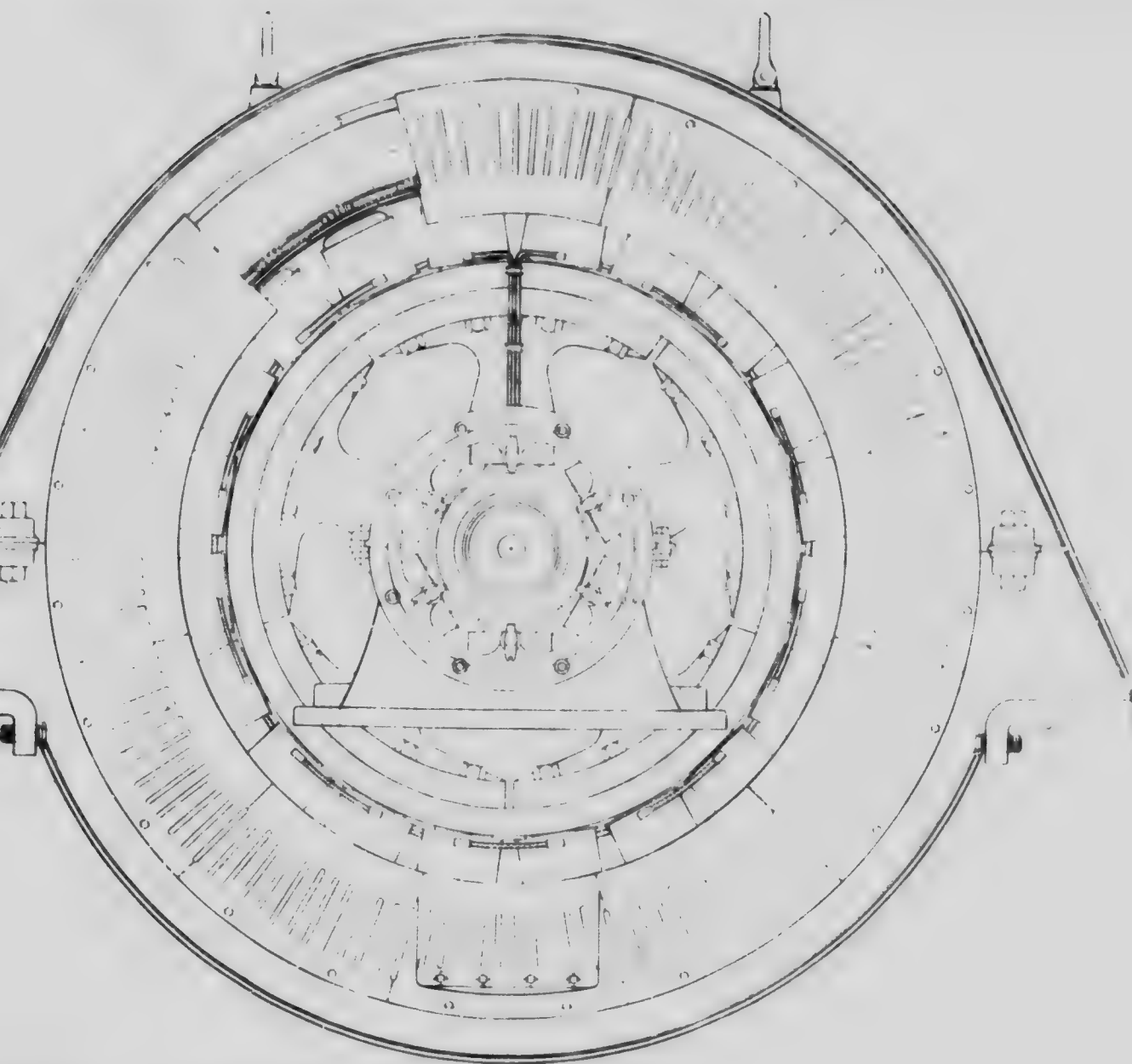


PLATE V

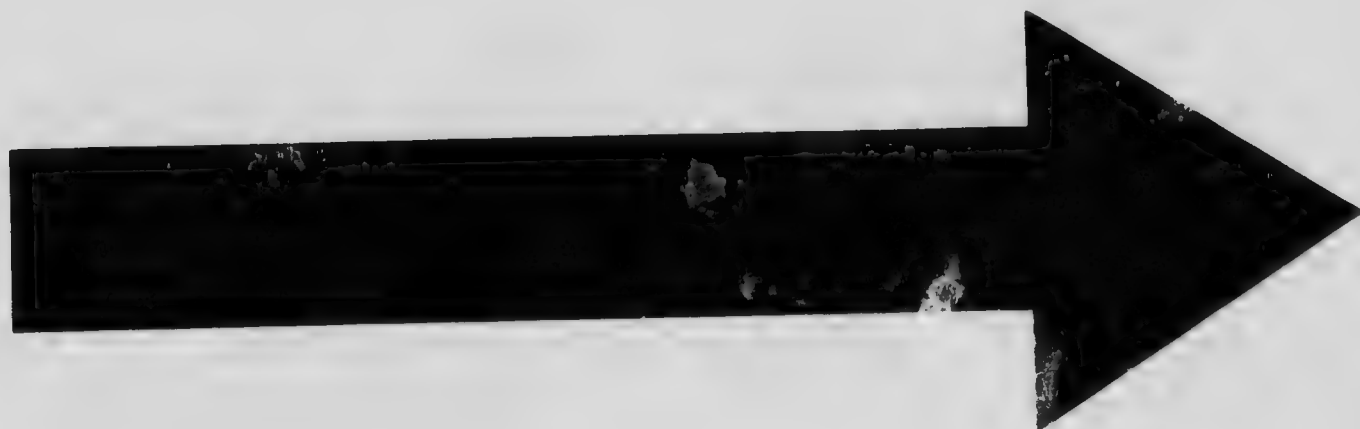


CROMPTON THREE-PHASE ALTERNATOR, 500 KILOWATTS (

(For full dimensions see diagrams and figures

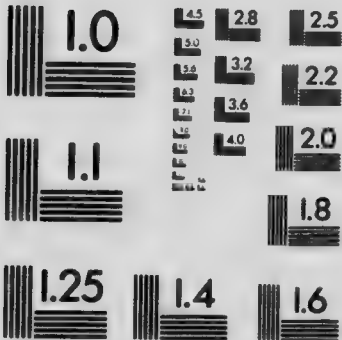


KILOWATTS (150 P. P. M.) AT 5,300 VOLTS.
(grams and figures in text.)



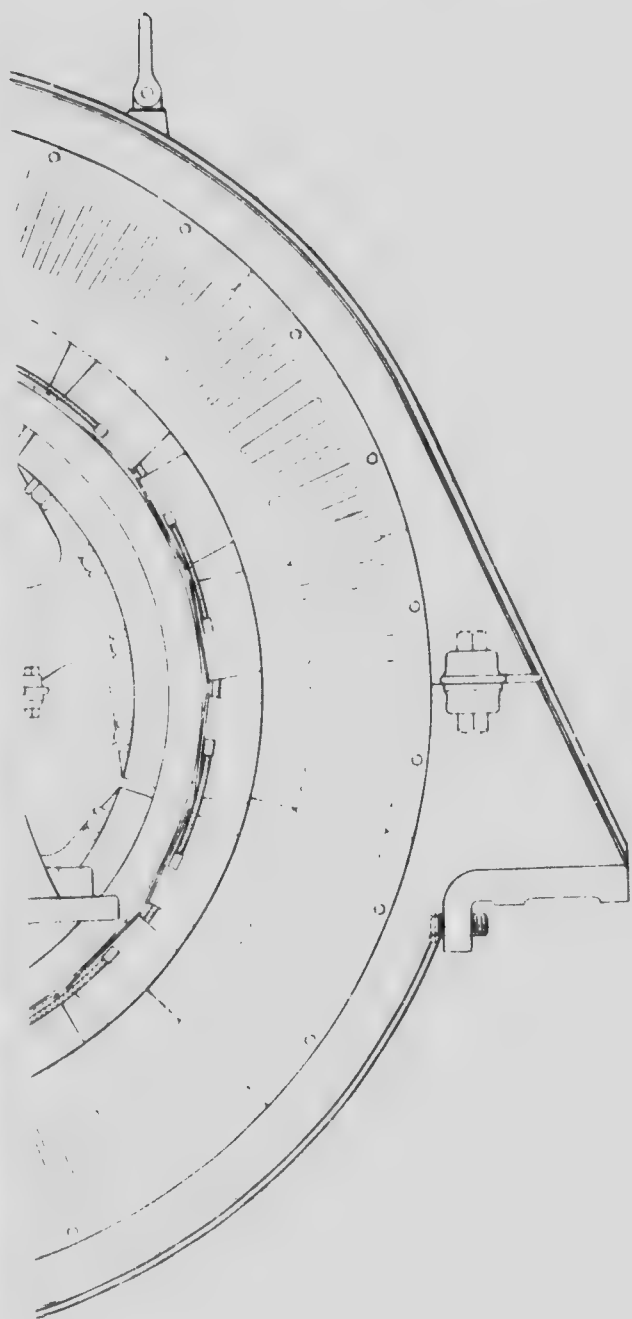
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which on an enlarged scale is a half-section at the hub end of one of the spokes.

Finally, as an example of the disc method, as distinct from the spoke method, of building up the rotor, a method applicable to smaller machines, Figs. 241 and 242 show the upper portion of a 300-kilowatt three phase alternator built by Messrs. Mather and Platt to run at 375 R. P. M. Fig. 241 is a half-radial section through the axle, and Fig. 242 is a drawing, partly in section, at right angles to the shaft. The rotor is a disc expanded into a very

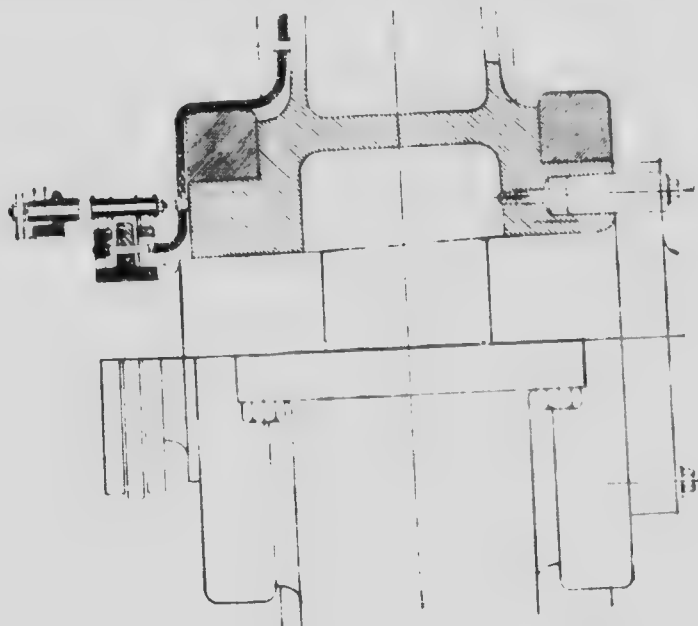


Fig. 240. Clamping of Hub of Brush Alternator on Shaft.

substantial rim at its outer periphery, to which the magnet cores are bolted with substantial bolts. The hub, disc, and rim are cast in one piece, the outer periphery of the rim having a diameter of 50 inches whilst the complete rotor has a diameter of 60 inches. For reasons already given the disc is pierced by eight holes, each 6 inches in diameter, the disc itself being about 2 inches thick. Further details of this machine will be given later.

As a further example of a machine in which the flywheel rim is divided Plate V. gives particulars of an alternator built by Messrs. Crompton and Co. for an output when running at a speed of 150 R. P. M. of 625 K. V. A. with a power factor of 0.8, equal to 500 kilowatts. The full load output is therefore

the same as that of the Dick, Kerr alternator referred to on page 246, but the speed is nearly double, and as the required periodicity, 25 Ω , is lower, the rotor

only carries 20 poles instead of 60, as in the preceding case. The two, if contrasted, are good examples of how speed and periodicity modify design. In the latter case the outside diameter of the completed rotor is 96 inches (8 feet), whilst the divided rim, to which the magnet cores are attached, has a diameter of $76\frac{1}{2}$ inches. Full details of the magnetic circuit of this machine and of its armature windings are given later (see pages 278 and 306).

The next point which it is of interest to examine is the method of attachment of the magnet cores or poles to the rim of the rotor, and it will be convenient at the same time to deal with the details of construction of these poles and their pole shoes or pole faces. As the power has to be transmitted mechanically from the shaft through these poles on its way to the armature circuits, it is evident that they must be mechanically, as well as magnetically, well designed.

In the Crocker-Wheeler case (Fig. 236) it has been already explained that the poles are solid, and are either cast solid with the rim or bolted to it. Many

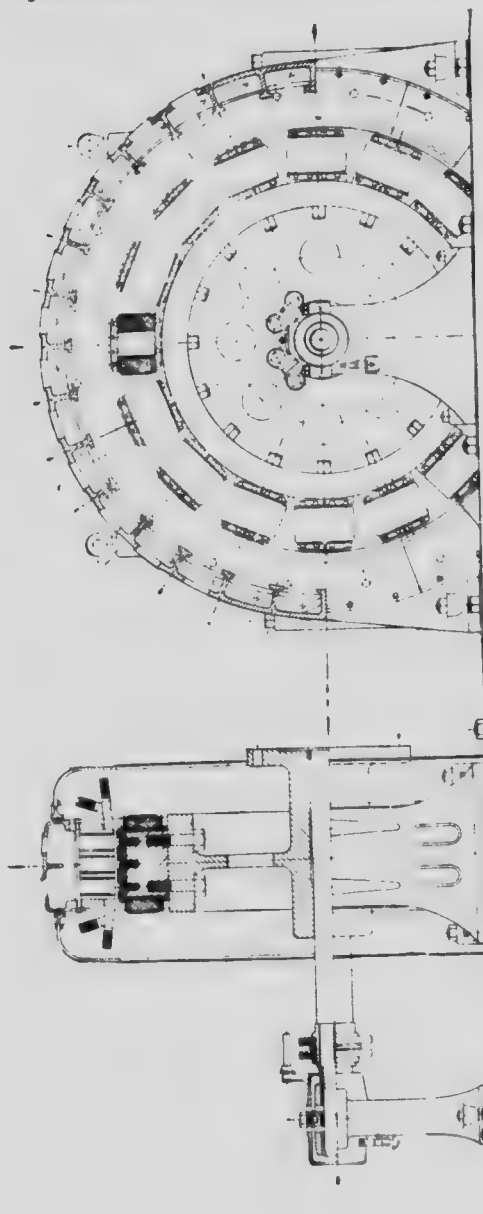


FIG. 244.

Mather and Platt 300-Kilowatt Alternator (at 75 R. P. M.)

FIG. 245.

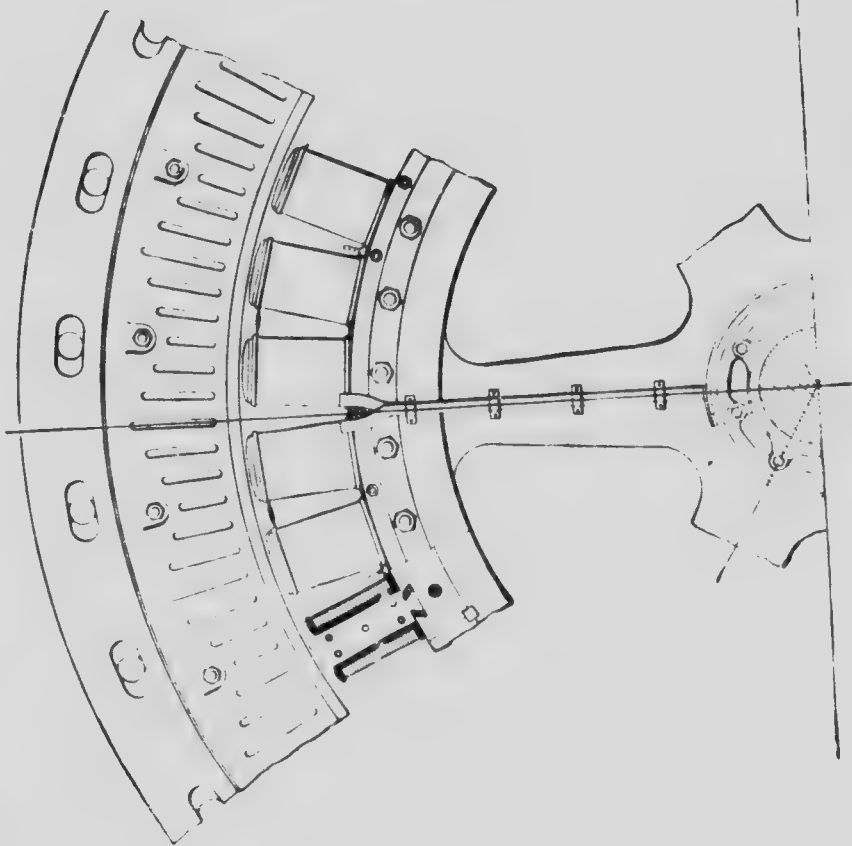


Fig. 243.
D.C.B. Kerr Field Magnets, with Illustrated Kerr Faces and Pole Faces.

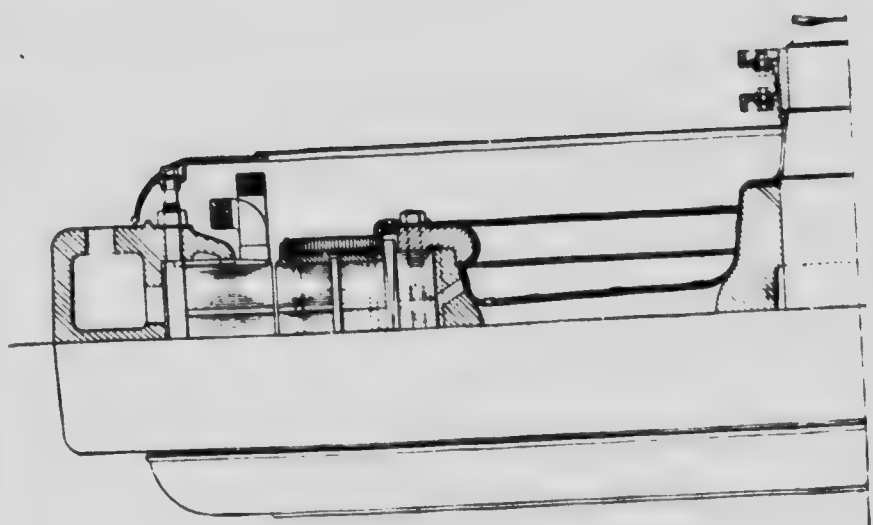


Fig. 244.

firms, however, adopt much more elaborate methods of construction, Messrs. Dick, Kerr and Co., for instance, having three standard methods, details of which are given in Figs. 243 to 248. Figs. 243 and 244 show, partly in section, two views of one spoke and the adjacent poles

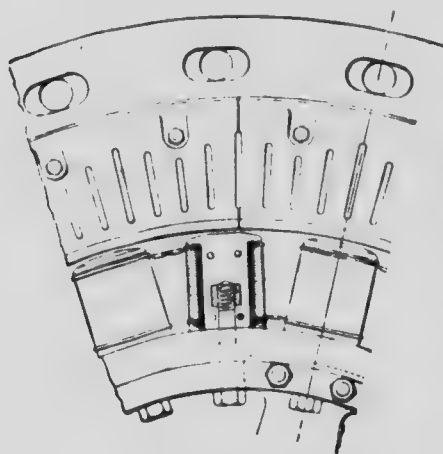


Fig. 245.

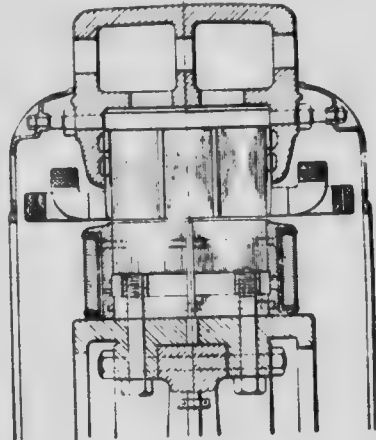


Fig. 246.

Dick, Kerr Field Magnets, with Solid Rim and Laminated Cores and Pole Faces.

of a 36-pole alternator. In this case the whole of the core and pole shoe is laminated, as is also the yoke behind, which is fixed on the flywheel spider by means of cast-iron flanges and machined bolts. The laminations

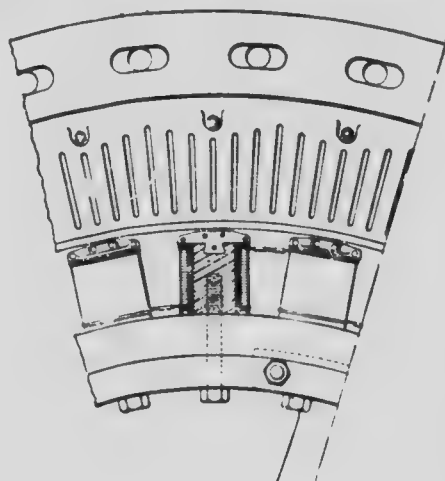


Fig. 247.

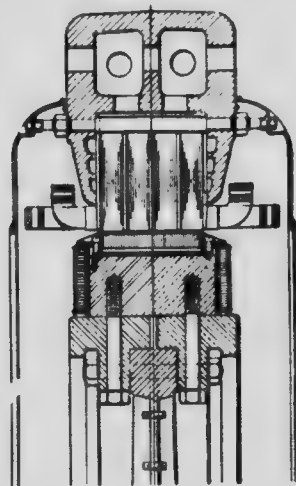


Fig. 248.

Dick, Kerr Field Magnets, with Solid Rim and Cores, but with Laminated Pole Faces.

of the yoke are dovetailed, and the core and pole shoe plates key into these dovetails as shown in the drawing. Ventilating spaces are provided through the poles at regular intervals, air reaching these spaces through special ducts in the spider, some of which can be seen in Fig. 244. It will be noticed that field coil and core can be removed in one piece by sliding parallel to the shaft along the dovetailed groove, as in the method adopted by the General Electric Company of America (see page 267). By such removal the armature coils can also be exposed readily for inspection and repair if necessary.

In Figs. 245 and 246, which show portions of the rotor of a 24-pole machine, the cores and pole faces are still laminated, but the rim upon which they are built is solid and consists of cast steel bolted firmly to the spider as shown. To this rim the laminated cores, which are held firmly together by cross bolts and end plates, are securely bolted by special bolts clamping solid rectangular cross pieces, since thin laminations would obviously not afford a firm grip for the screw thread of the bolt. This method of construction is used for large machines of low periodicity when the number of poles is not too large.

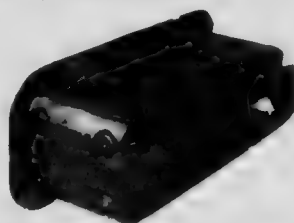


Fig. 244. G. E. Company Laminated Magnet Core and Pole Face



Fig. 250.—Rotor Spider ready to receive Magnet Core.

In the third method used by Messrs. Dick, Kerr and Co., and illustrated in Figs. 247 and 248, the magnet cores are solid, but carry laminated pole shoes, which are dovetailed and bolted into the cores after the exciting coils are placed in position. The cores are bolted to solid rims, which in their turn are bolted to the armature spider. This machine is a 32-pole machine.

A built-up laminated magnet core and pole face, designed and widely used by the General Electric Company of America, is shown in Fig. 249.

The stampings, like those in the Dick, Kerr machine just described (Fig. 244), are held together by massive end plates secured by four longitudinal bolts, and the finished core is so shaped that the dovetail at its base can be slid into a corresponding groove on the rotor spider. When all the cores are in place they are, in their turn, secured by two bolted-on end rings, as shown in Fig. 250, which depicts the spider before the cores are placed in position.

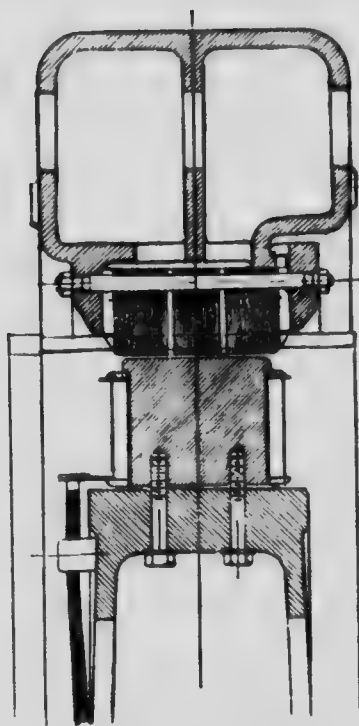


Fig. 251.—Section through Field Magnets of Brush 1,000-Kilowatt Alternator.

It is interesting to contrast this machine with the machine built by the same firm for the same output, 1,000 kilowatts, and periodicity, but running at 250 instead of 75 R. P. M. The number of poles is reduced from 80 to 24, and the diameter of the rotor from 101 to 244 inches. The higher speed machine is shown in Figs. 253 and 254. The flywheel rim is now cast solid with the hub and spokes, but the magnet cores and pole shoes are laminated and continuous, each core being

In the 80-pole 75-R. P. M. alternator, already partly described (see Figs. 238 and 239), the Brush Electrical Engineering Company use solid cores and pole shoes, as shown in Fig. 251, which is a section through the rim and one of the cores, together with the adjacent parts of the armature or stator, to which further reference will be made presently. Fully dimensioned details of these magnet cores and poles are given in Fig. 252, which also gives the chief dimensions of the flywheel rim. The cores are oval in section or, more accurately speaking, they are rectangular, with semicircular ends as shown in half plan at D, and each core is secured to the solid rim by two 2-inch bolts, $6\frac{1}{2}$ inches long. The rings for supplying the exciting current to the magnet coils are shown on the left-hand side of Fig. 238, and the exciting coils are wound with bare copper strip on edge, as explained on page 31, 1 inch wide by $\frac{1}{8}$ inch thick, there being 44 turns on each core.

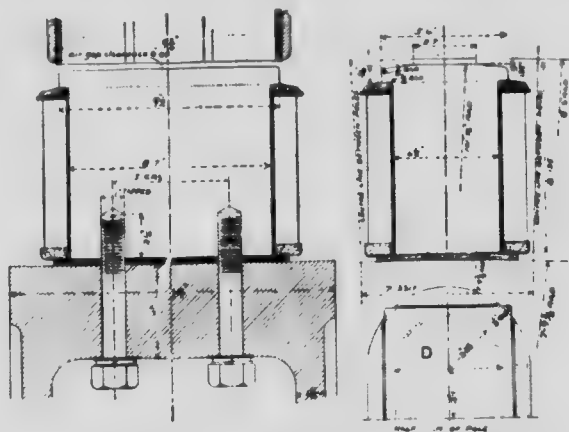


Fig. 252.—Details of Cores of Field Magnets of Brush Alternator.

bolted to the rim, as in a previous case, by special screws engaging with solid nuts embedded in the laminated core. These cores are not ventilated,

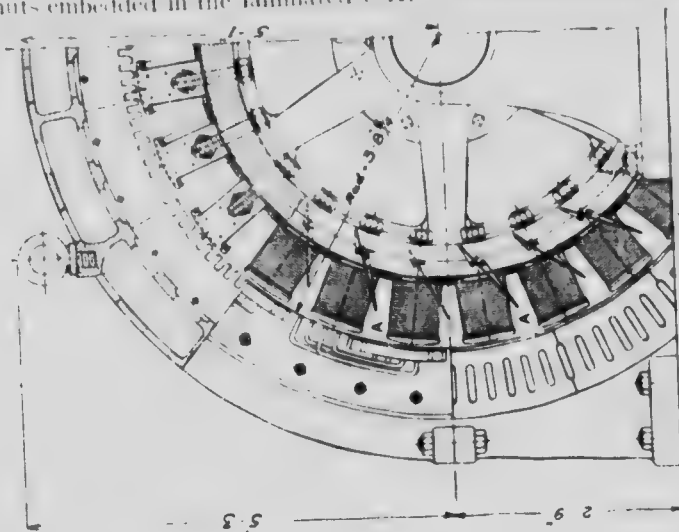


Fig. 434

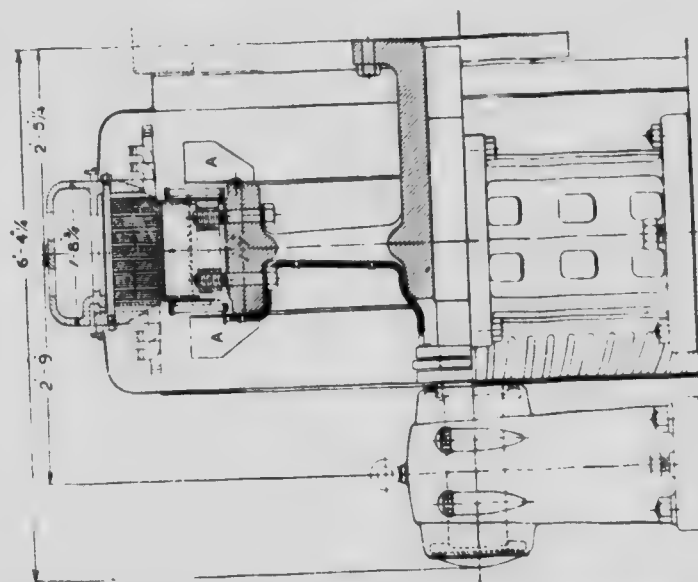


Fig. 435

Details of Irish 1,000-Kilowatt Alternator (350 R. P. M.)

as in some previous examples, but fan blades A A are attached at intervals on both sides of the rim, and these blow the air against the armature windings, thus helping to keep them cool. A picture of the completed rotor

is given in Fig. 255, which should be compared with Fig. 239, it being remembered that both machines are designed for the same output.

In the Mather and Platt 300-kilowatt machine (Figs. 241 and 242) the magnet cores are solid, each being fastened to the expanded rim of the disc by two substantial screws. They are provided with laminated pole shoes, each built up and held together between substantial end plates by four bolts, and then screwed to the end of the magnet core by three

screws. The pole shoes serve to hold the magnetising coils in position. The insulated rings for transmitting the current to the coils are shown mounted in Fig. 241. It may be noted here that the bearing pedestal on the left of Fig. 241 is placed sufficiently far from the stator ring, the shaft being made specially long for this purpose, to allow the whole stator to be slid along slides provided for the purpose, thus uncovering for inspection or repair the whole of the magnets and the armature wind-

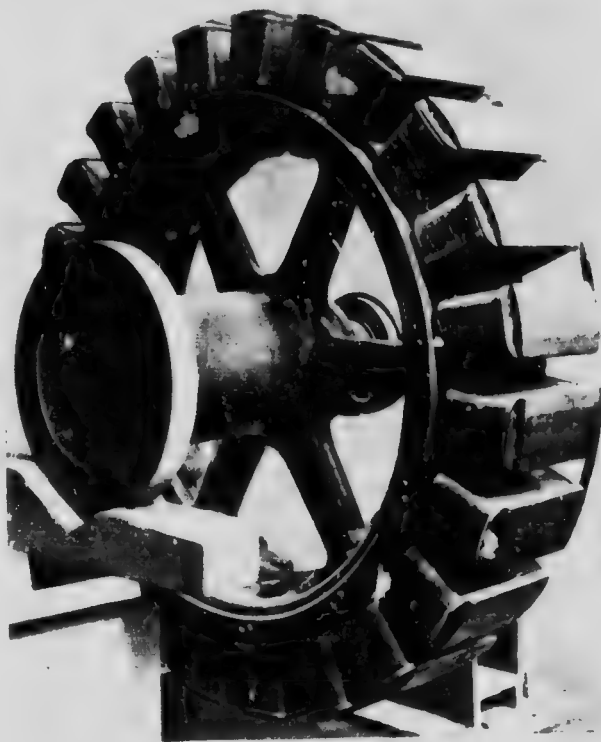
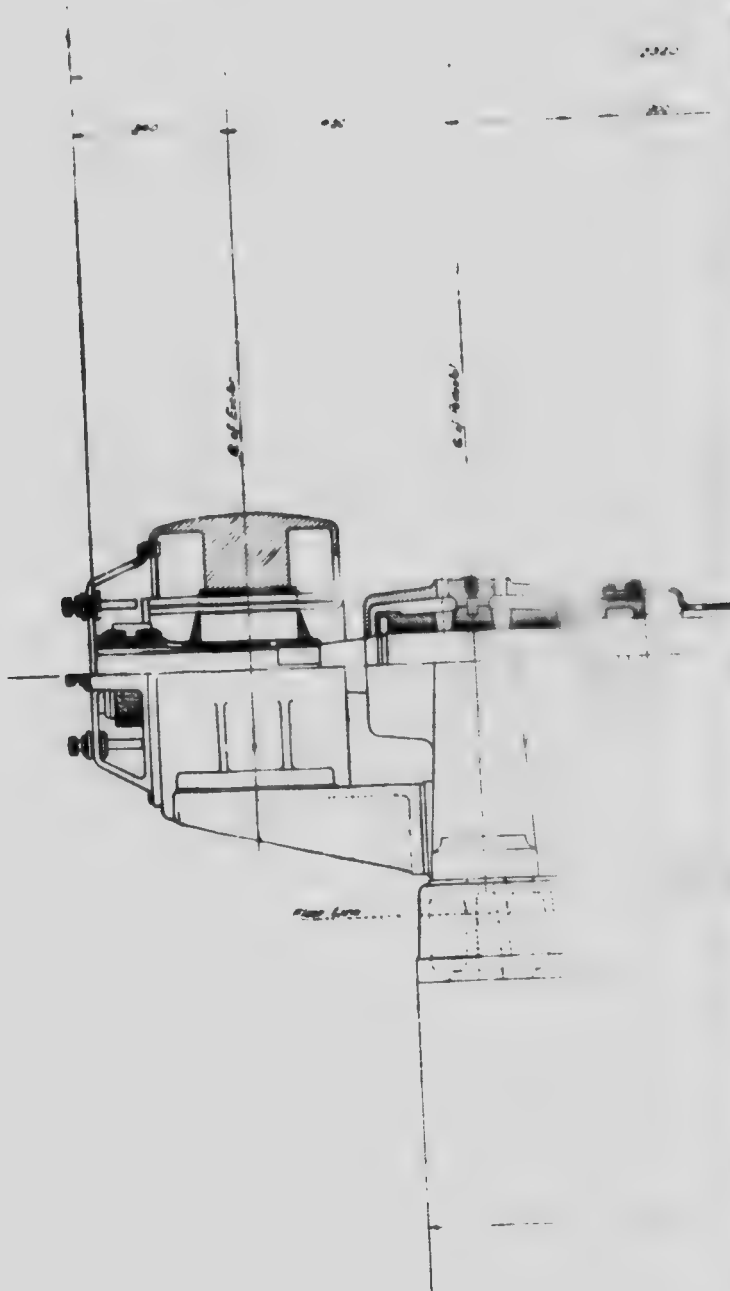


Fig. 255.—Rotor of Brush 1,200-Kilowatt Alternator (250 R. P. M.)

ings. The half-coupling on the right is for direct connection to the shaft of the driving engine.

As a final example, Plate VI. gives similar details of a 250 K. V. A. 230 volts 16-pole machine built by Messrs. Bruce Peebles and Co., to run at 375 R. P. M. A disc well pierced with holes is used as the foundation of the rotor, and solid cores and pole faces are bolted to it. Other details can be made out from the drawing, upon which some of the chief dimensions are marked in millimetres. It should be compared with the other drawings both for points of resemblance and of difference.



Water-Driven Alternators.—The water-driven turbines, whether of the reaction or the impulse type, in practical use for driving electrical generators, run at a much lower speed than steam-driven turbines, and, therefore, the alternators which they, in their turn, drive, approximate to the machines already dealt with in the immediately preceding pages rather than to the "turbo-alternators," which will be described presently. In fact, the water turbines run at the speeds commonly covered by the speed range of recipro-

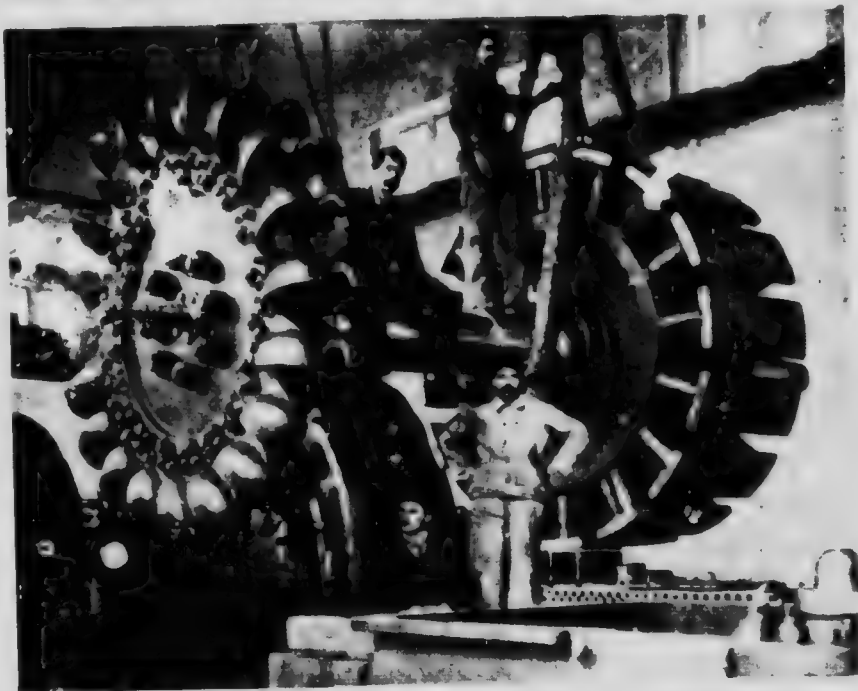


Fig. 256.—Rotors of Turbine and Generator for 5,250-K. V. A. Set at the Löntsch Generating Station.

cating steam engines. The chief difference is that some of the water turbines, especially, though not necessarily, those of the reaction type, drive vertical shafts, and for these special machines, if directly coupled to the shaft, must be designed: Many water turbines, however, are mounted on a horizontal shaft, and therefore it will be well to describe briefly both types of alternators which, in practice, are invariably of the rotating field-magnet type.

(a) **Horizontal-Shaft Hydro-Alternators.**—The rotating part or completed rotor of one of these sets is very graphically shown in Fig. 256, which is reproduced from a photograph taken during the erection of the machine in the hydro-electric generating station in the Löntsch, in Switzerland. At the

machines of very much lower output. It will be noted that the external diameter of the housing is 3.9 metres (12 ft. 9 in.), and that of the rotor 2.48 metres (8 ft. 1½ in.), whilst the air-gap clearance is 1 cm.; the axial length of the armature iron is 1 metre (39.4 inches), and its radial depth 30 cms. (11.8 inches). The exciter is driven by the same shaft, and is carried on a bracket overhanging from the outer bearing. The massive character and the details of the pedestals and bearings should also be noted.

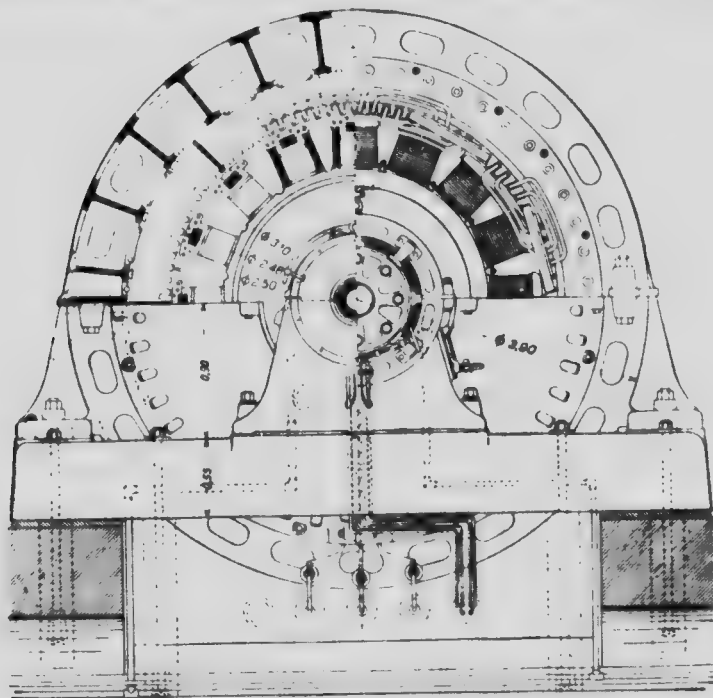


Fig. 253.—Brown, Boveri Hydro-Alternator, 5,250 K. V. A. at 375 R. P. M.

The complete set as installed in the Löntsch power station is shown in Fig. 259, the height of the generator above the floor being 3.4 m. (11 ft. 2 in.), and its width 4.75 m. (15 ft. 7 in.).

(b) *Vertical-Shaft Hydro-Alternators.*—For driving large alternators from turbines running on a vertical shaft, the most convenient plan is to build the alternator with its shaft also vertical, and to couple one shaft directly to the other. This plan has been adopted in many power stations in which the separate units are dynamos, whether for continuous or alternate currents, with outputs running into hundreds or thousands of kilowatts. The machines are of the rotating field type, and Fig. 260 gives a section of one with an

output of 3,750 kilowatts, or 5,000 H. P., erected some years ago in the large power station at the Falls of Niagara.

The figure, to a great extent, is self-explanatory. It will be noticed that the rotating field magnets surround the armature, being supported by a cone-shaped driver, which is keyed to the top of the upright shaft. This arrangement has caused these machines to be known as of the "umbrella" type. The magnets are 140 inches in diameter, and are rotated with an angular velocity of 250 R. P. M., which gives a peripheral speed of 9,000 feet (or 1.7 miles) per minute. The yoke ring is of nickel steel, and the twelve field poles are of solid cast-steel with extended pole faces as shown. The exciting coils are wound with copper strip, 1 inch by

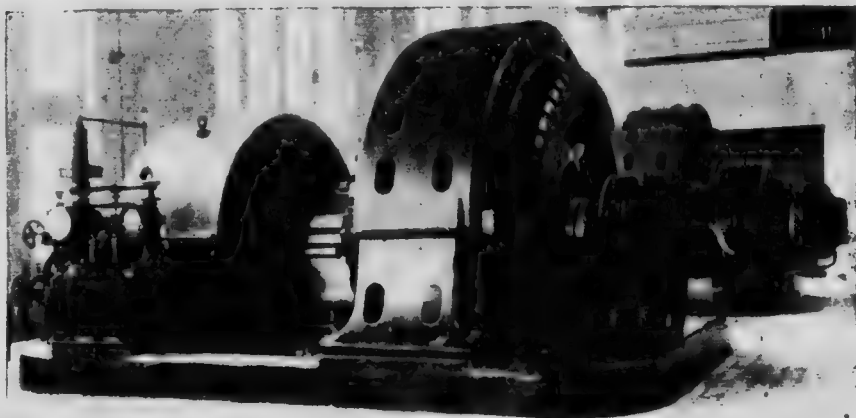


Fig. 259.—Water Turbine, 6,000 H.P., driving Brown, Boveri Alternator of 5,250 K. V. A. at 375 R. P. M.

$\frac{1}{8}$ inch, set on edge in four layers, between which ventilating passages are secured by appropriate distance pieces. The exciting current varies from 50 to 80 amperes, according to the load; and as the resistance of the circuit is $1\frac{1}{2}$ ohms, the total power lost by heating at full load is about 10 kilowatts, or 0.28 per cent. of the load. The current is led into the rotating field through slip rings, which can be seen at the top of the machine.

The armature is stationary, and is built up from the floor of the dynamo room round the central shaft. The housing into which the laminated core discs are dovetailed is hollow, and to carry off the heat when the machine is running, water is continually circulated through the passages shown on the left of the figure. For although the efficiency of the machine is 98 per cent., the 2 per cent. lost in heat requires the dissipation of 75 kilowatts, or 100 H. P. Of this about 61 kilowatts are accounted for by the copper and iron losses of the armature, hence the necessity for special arrangements

for keeping the machine cool by carrying off the heat generated: The armature core discs are provided with twelve of the usual air ducts, each half an inch wide, and are securely clamped in their places by end plates locked to an upper spider. The air gap between armature and

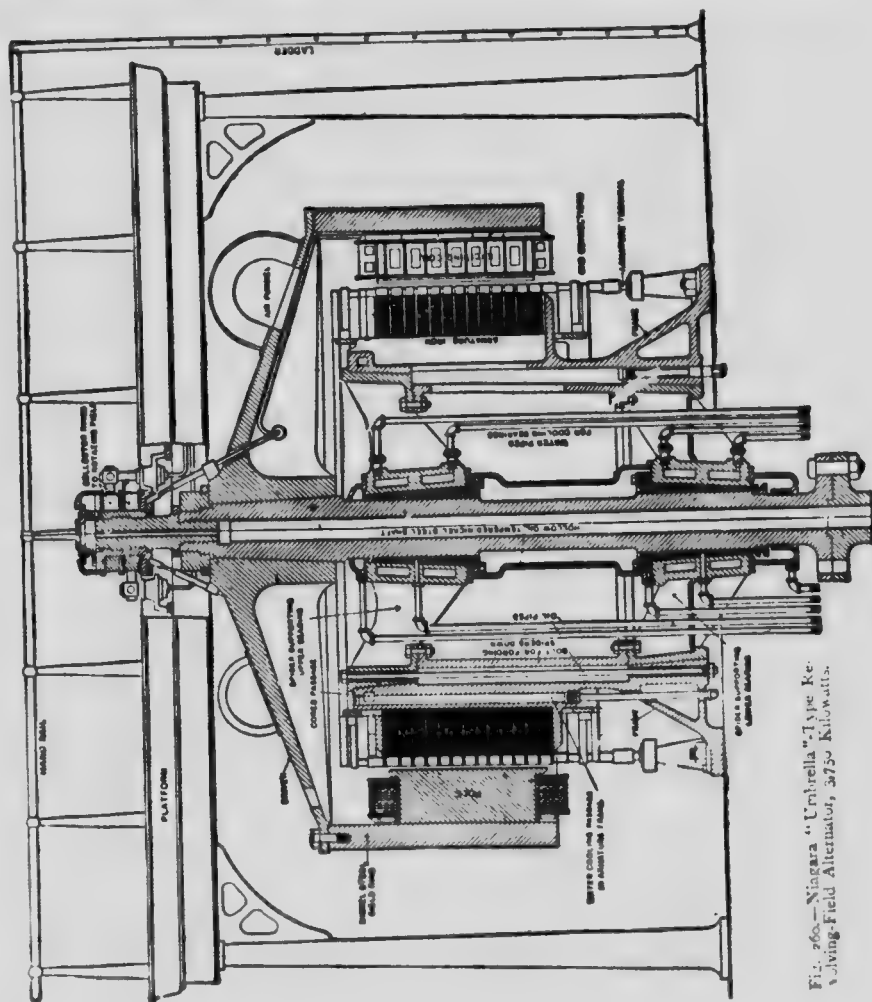


FIG. 260.—Nagara "Umbrella" Type Re-
versing-Field Alternator, 3,750 Kilowatts.

field pole face is $\frac{3}{4}$ inch wide: There are 322 slots, each containing one conductor, with a cross-section of 2 inches by $\frac{3}{4}$ inch. The output of 3,750 kilowatts is in two-phase currents at 2,000 volts pressure between the conducting lines.

The upper and lower bearings are lubricated by oil pumped through the oil pipes shown on the left-hand side of the figure, and are further kept cool by water circulated through the pipes and passages shown on the right-hand side. By the oil the heat generated in the journals is reduced to a minimum, and the circulating water carries this heat away before it can raise the temperature to a dangerous point.

An external view of one of these machines, as erected in the works,



Fig. 261.—Earliest Pattern of Niagara "Umbrella" Type Alternator in Erecting Shop.

of the Westinghouse Company at Pittsburg, before being sent to Niagara, is shown in Fig. 261.

In more recent machines, instead of the field rotating outside the armature, the latter is placed in the same position as in horizontal-shaft alternators, namely, outside the field. The external appear-

ance of a large American machine of this type has been illustrated at page 227 (Fig. 218), and a European one, built by Messrs. Brown, Boveri and Co., is shown in Fig. 262. The latter machine has a three-phase output of 7,000 kilowatts at 50 ω when running at 300 R. P. M. It is 16 feet 10 inches in diameter, measured to the outside of the shell of the stator housing, or 18 feet 8 inches overall if the strengthening ribs which support the brackets which carry the top gear are included. The total height of the machine above the floor of the station after erection is 16 feet 2½ inches, of which 104 inches is the vertical height of the alternator section, the remaining 90½ inches being added by the continuous current exciter and its mountings. The inner diameter of the stator is 12 feet 3½ inches, and the over-all diameter of the rotor is 12 feet 2½ inches, so that the air gap is about ½ inch wide, measured radially, its exact width being 0.47 inch. The vertical height of the laminated core of the armature is 36 inches, which is a much longer axial length in comparison with the diameter

than is usual with steam-driven slow-speed alternators. Many details of construction are, however, similar to those already described for steam-driven plant. The upper bearing of the vertical shaft is carried by the six substantial brackets which can be seen projecting inwards in Fig. 262, and these also carry the field magnets of the exciting dynamo, whose



Fig. 262.—Brown, Boveri Modern Hydro-Alternator, 7,000 Kilowatts at 300 R. P. M.

armature is carried on an extension of the vertical shaft. The housing of the field magnets of this machine is 59 inches in diameter, and there is an upper platform to enable the attendant to adjust the brushes and do other necessary work. Brackets project inwards below the level of the rotor to support additional bearings and the gear for driving the governor.

Full details of a vertical shaft water turbine-driven alternator built by the same firm are given in Figs. 263 and 264. The machine differs from the alternator illustrated in Fig. 262, in the form of the housing of the

armature or stator, and also in not carrying its exciter on the end of the shaft above the field magnets of the alternator. This simplifies the design by dispensing with the supports necessary for the field magnets of the exciter and in other ways: The figures give all the principal dimensions, Fig. 263 being a vertical section through the shaft, and Fig. 264 a horizontal plan partly in section. In addition to the dimensions being marked on the drawing, a scale is given with Fig. 263, but this scale does not apply to Fig. 264, which is drawn to a slightly larger one. The machine is designed for an output of 1,000 kilowatts at 50 Ω when running at 120 R. P. M.

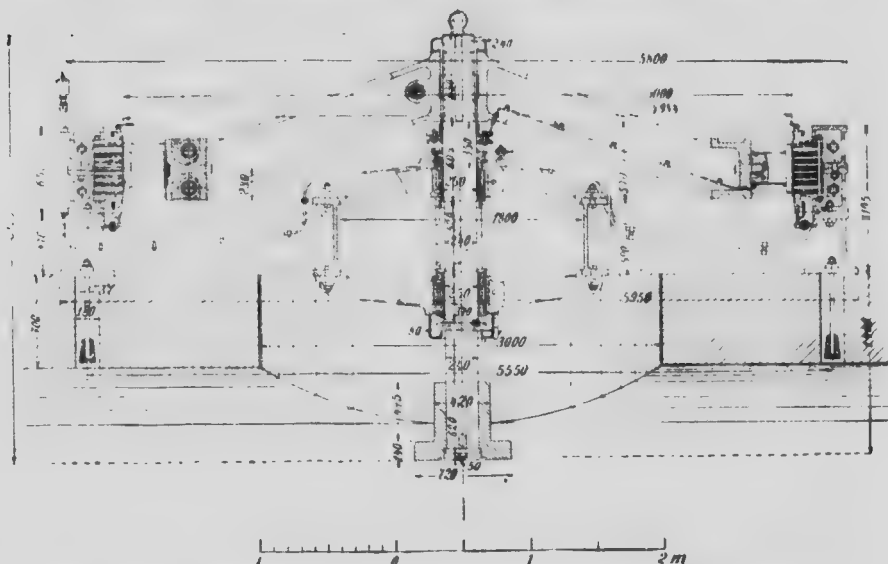


Fig. 263.—"Umbrella"-Type Revolving Magnet Water Turbine-Driven 1,000-Kilowatt Alternator (120 R. P. M.).

It will be noticed that the rotating ring is supported by twelve spokes sloping downwards from a central hub or cap at the top of the shaft, which is held in place lower down by vertical bearings, supported by spokes projecting radially inwards from a frame, bolted to the foundations and carrying the housing of the armature. The rotor spider so built is usually referred to as being of the "umbrella" type, though the applicability of the title is not so strong as in the alternator shown in Fig. 261. In the present case the rim is U-shaped, and the spokes have a T cross-section, the object being to obtain stiffness and strength combined with lightness. The magnet wheel to which the cores are bolted is built in two halves bolted together, and has an over-all diameter of 4.4 m. (14 feet 5 inches). The cores and pole faces, made of wrought steel, are solid, and each in one piece, and the completed field magnet has a finished diameter of 4.988 m. (16 feet 4 inches);

it revolves inside the armature, whose internal diameter is exactly 5 m., and therefore the air-gap clearance is only 6 mm. (0.236 inches), which requires very careful workmanship on so large a machine to ensure that it shall be accurately the same everywhere. There are in all 50 poles, the cores being each wound with 61 turns of copper strip, 20 mm. wide, and 3.5 mm. thick, insulated with layers of paper. A complete rotor, as assembled in the workshops, and ready for keying to the shaft, is shown in Fig. 265; the "umbrella" appearance is very marked when it is remembered that the shaft upon which it is to be mounted is vertical. The over-

all diameter of the stator is 5.8 m. (19 feet), its vertical height above the supporting bed plate being 0.65 m. (25.6 inches). The iron of the magnetic circuit is of course laminated, and is well provided with ventilating ducts, and there are 150 slots (3 per pole), each 50 mm. wide. This gives one slot per pole per phase, and, anticipating winding details, which are the subject of the next section, it will be convenient to record here that each slot contains seven conductors, each conductor consisting of 37 strands of

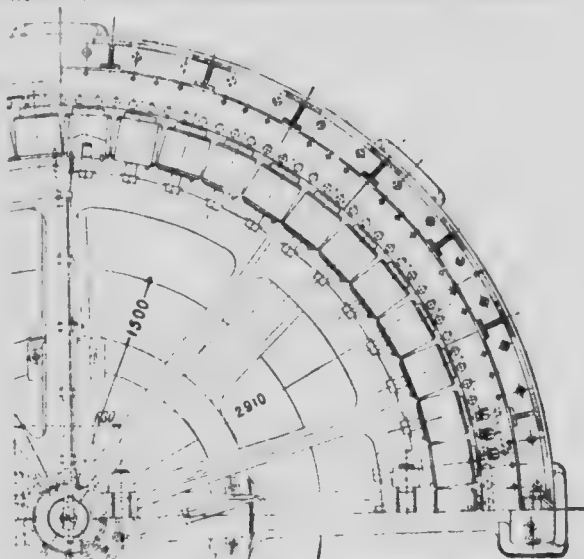


Fig. 264.—Part Plan and Section of "Umbrella"-Type 1,000-Kilowatt Alternator.

1.5 mm. wire, the whole of the conductors of each phase being connected in series and the phases connected in "star."

Some of the machines of this type present a much flatter appearance than that shown in Fig. 265. This is especially the case with some of the large very slow-speed machines used in some of the American hydro-electric stations. An instance is given in Fig. 266, reproduced from the *General Electric Review*, which shows the usual appearance of a three-phase machine built by the General Electric Company of America, to give 9,000 kilowatts at 11,000 volts between phases when running at 57.7 R. P. M. The rotor of this machine resembles those of slow-speed steam-driven machines, except in regard to axial length, which is much greater.

For machines of very large output, running at much higher speeds, the same company designs the rotors of a general type, which may be described

as intermediate between flywheel slow-speed rotors and the rotors of salient-pole steam turbo-alternators. Great care is taken in the design of the spider, which is built up in sections at right angles to the shaft, and

made either of cast or rolled steel. In both cases the object is to ensure greater uniformity and homogeneity in the material. A field-magnet spider of this type, built in three sections, is shown in Fig. 267. It is for a machine with a full load output of 10,000 kilowatts at 11,000 volts when running at 400 R. P. M.

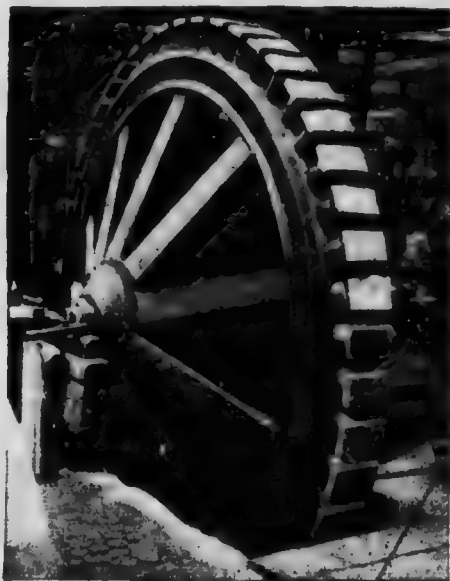


Fig. 265.—"Umbrella"-shaped Magnet Wheel in Workshop.

In Fig. 268 the sectioning is carried farther, for the spider illustrated is built up of rolled steel plates, firmly bolted together as shown. This spider is also for a 10,000 kilowatt machine, but because of the smaller number of poles has to run at a higher speed, namely, 514 R. P. M.

Both the spiders just described are finished on their peripheries with longitudinal grooves intended to receive a carefully constructed dovetail on the lower end of the pole core. The pole core and face is of the type shown in Fig. 269. Owing to the sharp curvature of the spider, the angles of the dovetail have to be carefully calculated so that the necessary strength shall be secured in the finished rotor, for it must be remembered that both magnetically and mechanically the joint must be very sound. The core and pole face are built up of the usual laminations, which do not conduce to stiffness, and the magnetising coil,

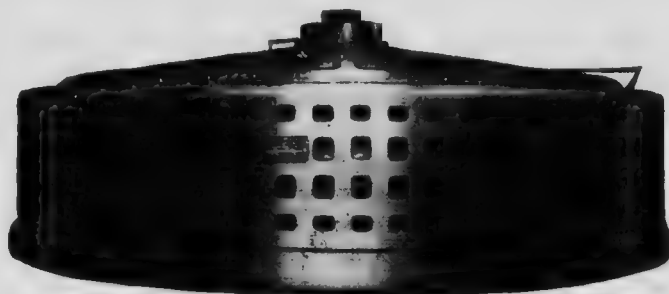


Fig. 266.—Very Slow-Speed (57.7 R. P. M.) 9,000-Kilowatt Hydro-Electric Alternator.

for it must be remembered that both magnetically and mechanically the joint must be very sound. The core and pole face are built up of the usual laminations, which do not conduce to stiffness, and the magnetising coil,

as will be seen in the lower figure, overhangs by a fair amount. The last-named three figures are also reproduced from the *General Electric Review*.

The above examples will probably be sufficient to accentuate both the resemblances and the differences between fuel-driven and water-driven slow-speed alternators of the multicoil field type.

Monocoil Fields.—

Taking up next the machines with single exciting coils on their field magnets, it may be remarked at the outset that alternators with such magnets are rapidly becoming of historical interest only, and therefore our references to them here will be brief. Machines of this kind with fixed magnets and with rotating armatures, have not been constructed, though mechanically, electrically, and magnetically it is possible. The reasons already given for fixing the armature in

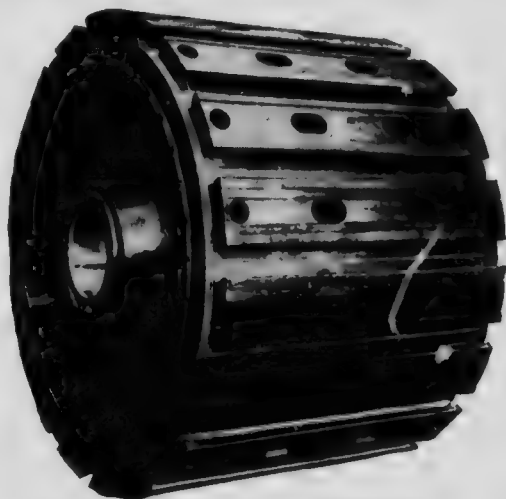


Fig. 267.—Cast-Steel Spider for 10,000-Kilowatt (400 R. P. M.) Alternator.

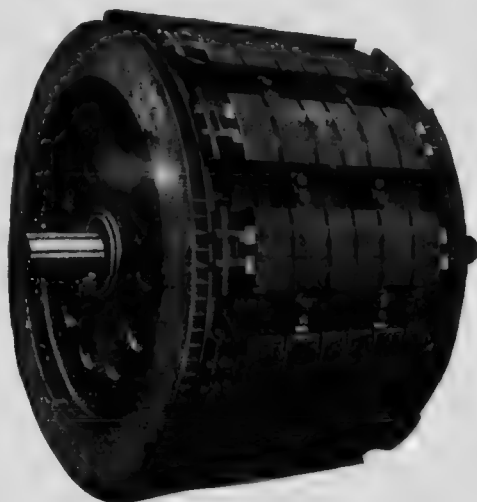


Fig. 268.—Spider built of Rolled Steel Plates for 10,000-Kilowatt (514 R. P. M.) Alternator.

the case of multicoil fields are strengthened in the present case by the inutility of going to the trouble of designing a fixed monocoil magnet. We pass therefore to the case of revolving fields, leaving inductor alternators, which form an apparent exception to the above statement, to be dealt with separately.

Rotating Monocoil Field Magnets.—The prototype of all multipolar alternators with a single exciting coil is the Mordey alternator, first produced in 1888, and which in its original form is now quite historical. The field magnet, which



Fig. 269.—Field-Magnet Cores and Coil for 10,000-Kilowatt (400 H. P. M.) Alternator.

has already been described in the chapter on electro-magnets (see Fig. 302, page 338, Vol. I.), has its one exciting coil wound on a core from which there radiate polar projections which are curved round so as to form two opposed

crowns of poles, such that all the poles on one side are of north polarity,

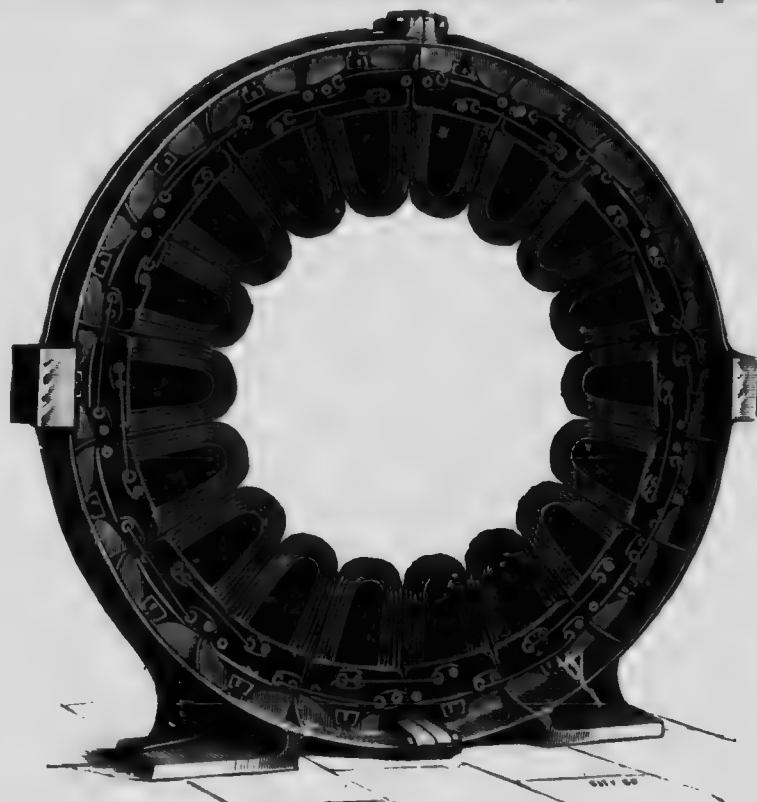


Fig. 270.—Armature of Mordey Alternator.

and all those on the other side are of south polarity. In the machine illustrated (Fig. 271), which had an output of 37.5 kilowatts, there were nine of these poles on each side, and the two sides approached within

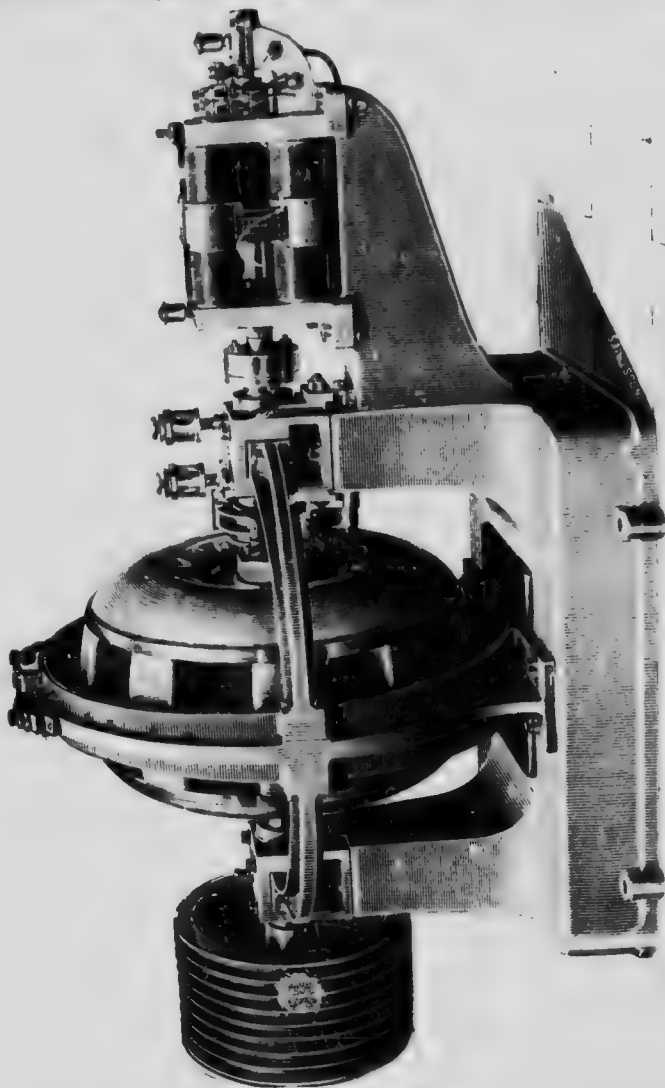


Fig. 271.—The Mordey Monocoil Field Alternator, with Exciter.

three-quarters of an inch of one another. In the narrow gap thus left the stationary armature coils, which are shown in Fig. 270, were placed: There were eighteen of these coils, wound with ribbon copper, 0.45 inch

wide, on porcelain cores, and clamped at the broad end to a light but firm frame, the ends of the conductors of each coil being brought out through porcelain insulators and suitably connected together. Since there were twice as many armature coils as there were poles on one side of the field magnet, it follows that if one coil were exactly in the gap between two opposed poles its neighbours on either side were quite clear of these gaps; the magnetic flux through the first coil was, therefore, a maximum, whilst the flux through the adjoining coils was a minimum. As the field magnet revolved the relative positions of the poles and the armature coils changed rapidly, and the number of magnetic lines of force passing through any one of the latter was continually varied from a maximum to a minimum, and back again to a maximum, and so on. These variations caused alternating E. M. F.'s to be set up in the coils, and these by suitable connections could be thrown into an external circuit. The action of the machine, therefore, differed from those previously described, inasmuch as the currents were produced by *variations* only of the magnetic field in which any individual coil was placed, whereas in the other machines the currents are induced by *variations and rapid reversals* of the field.

In the complete machine (Fig. 271) the field magnet was to a great extent hidden by two metallic shields, whose object was to diminish the air currents which would otherwise be set up by the rotating pole pieces. The field magnet was excited by the current from a small Victoria dynamo, usually placed, as shown in the figure, on the same shaft as the alternator: Thus excited, the machine gave a current of 17 to 20 amperes at a potential difference of 2,000 volts when running at 650 R. P. M. It should be specially noticed that there was no iron in the armature of this dynamo, a fact to which Mr. Mordey attached great importance, as allowing several machines to be coupled together without inconvenience, and also as having an important bearing on its use as a motor and on its efficiency.

The type was at one time a favourite one with manufacturers, and went through many mechanical and other modifications at the hands of Mr. C. E. L. Brown, of the Oerlikon Works, Professor Kapp, Messrs. Johnson and Phillips, Messrs. Ferranti, Ltd., and others, as well as by the Brush Electrical Engineering Company, which manufactured the original Mordey machines. The most interesting of these modifications was perhaps the "claw" type, in which the poles faced radially outwards, instead of axially, from the revolving hub, and were surrounded by a "housed" armature which was not unlike a modern multipolar stator. Descriptions of various typical machines and a dimensioned drawing of a "claw"-type alternator will be found in the previous editions of this book. Machines excited in this way have been superseded by machines with multicoil excitation, which is better adapted for the large units now demanded, and which has other advantages.

It will suffice for our present purpose to show in Fig. 272 one of the latest

forms of the original Mordey machine as installed, in 1900, at the Wandsworth generating station of the County of London Electric Lighting Company. The machines were each of 180 kilowatts capacity, giving single-phase currents at 2,000 to 2,200 volts and 100 periods per second. The changes in mechanical design rendered necessary by increased size and greater experience in working can

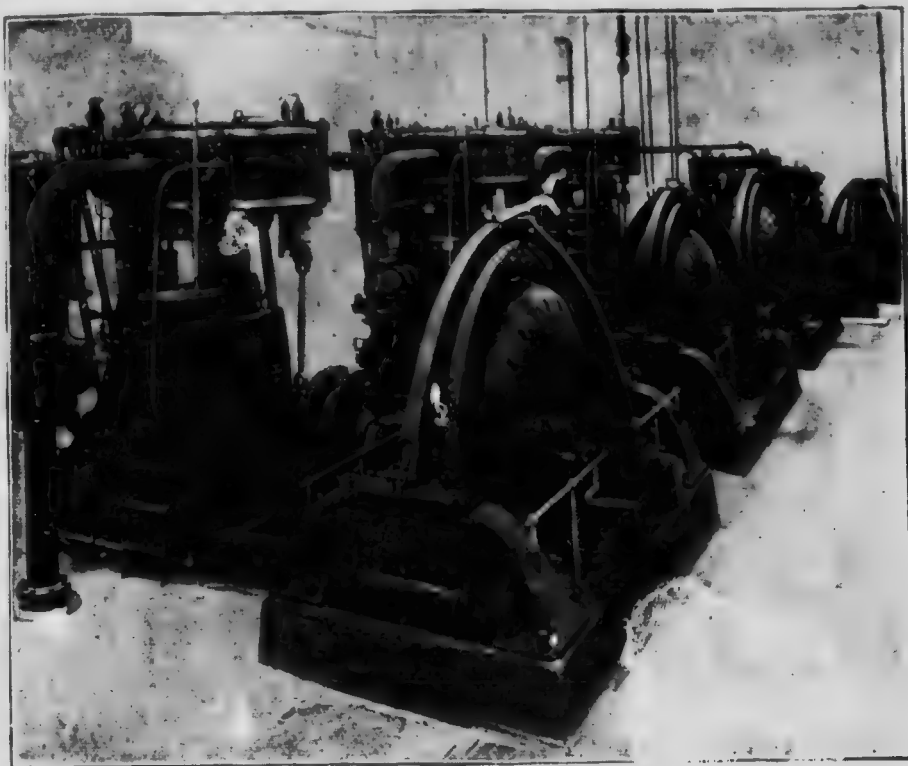


Fig. 272.—Mordey Monocoil Field Alternators.

be traced by comparison with Fig. 271. The most prominent of these is the stay which, springing from the pedestal, gives rigidity to the frame from which the armature coils project inward. As the distance between the opposed faces of the polar projections is small, and the armature coils occupy the greater part of the space, the necessity for very exact workmanship and rigidity of design is apparent. In fact, some earlier machines in which the clearance was only $\frac{1}{4}$ inch on either side had to have this distance afterwards increased. It will be noticed that the shield was pierced with holes; the object of these was to drive cold air against the armature coils,

and so to assist in keeping them cool. In some machines little cowls were fixed at the outer ends of the holes to catch and deflect the air more effectually.

Inductor Alternators.—Although machines of this type are not now it is believed, manufactured by any of the principal manufacturers of large machines, their supersession is so recent that many must still be in use in generating stations, and they also offer certain points of interest which justify some little space being devoted to them. Theoretically, they can have either the multicoil or the monocoil method of excitation.

(i.) *Multicoil.*—This form is entirely of historical interest, the only actual

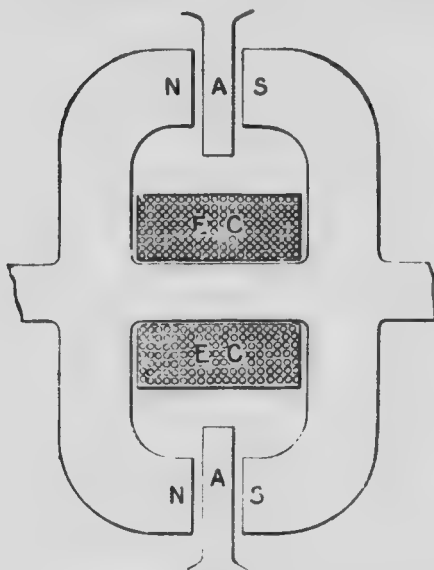


Fig. 273.

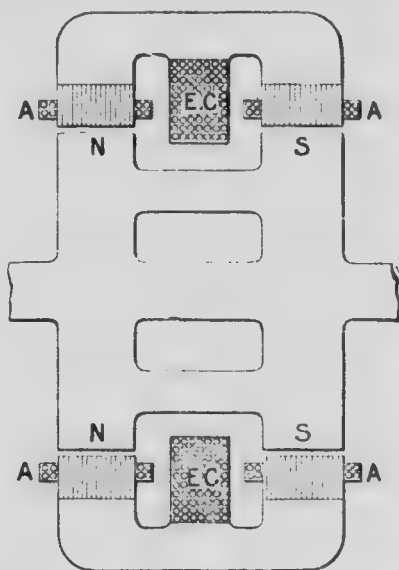


Fig. 274.

Diagrams showing Positions of Revolving and Fixed Exciting Coils for Monocoil Field Magnets.

machine with which the writer is acquainted being designed by Kingdon, and built by Woodhouse and Rawson in 1888. The output was only 50 kilowatts at 350 R. P. M., and to produce this the inductor wheel was 53 inches in diameter and 12 inches wide. It will be found illustrated and described in the last edition.

(ii.) *Monocoil.*—More recent inductor machines, instead of having a multicoil field magnet, as in the early machine of Kingdon, were usually of the monocoil type, and as such may be regarded as a natural development of the monocoil revolving field magnet machine of Mordey, described on pages 267 to 271. In that machine the magnetic flux across the gap in which the armature coils were fixed would be the same, whether the exciting coil were rotating with the polar projections, or were itself stationary whilst

only the hub and the polar horns revolved. If, therefore, it could be arranged to support this exciting coil from the inner ends of the fixed armature coils, the inductions in the latter would not be affected, provided that the excitation as measured in ampere-turns were unaltered. The two arrangements are shown diagrammatically side by side in Figs. 273

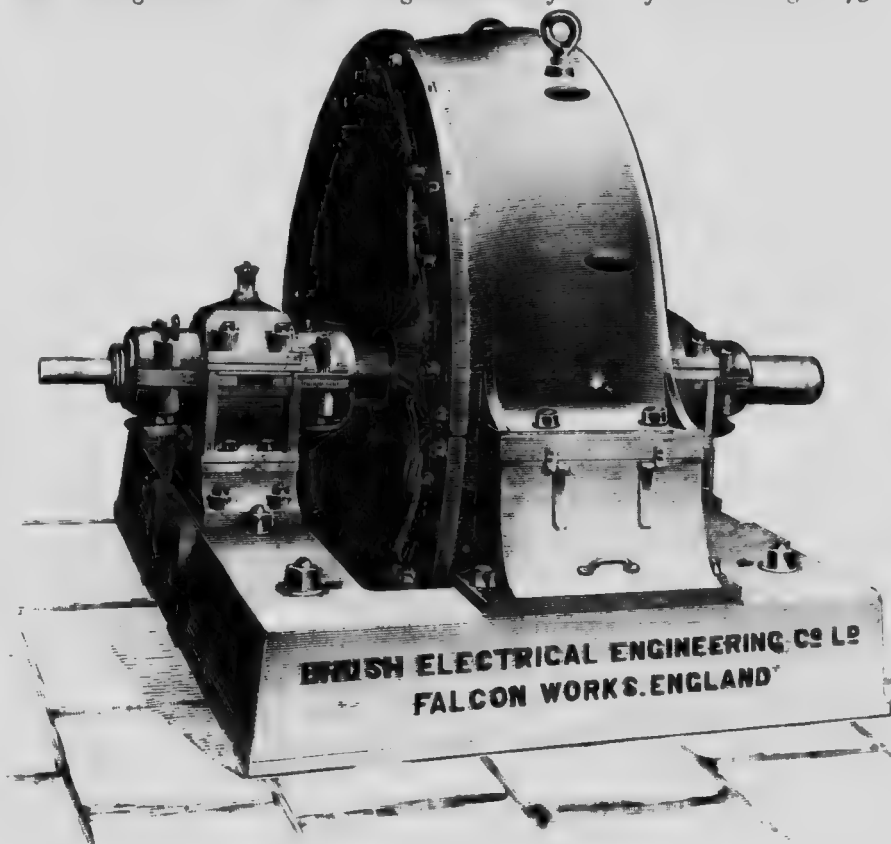


Fig. 275.—Mordey Inductor Alternator, 100 Kilowatts.

and 274. In Fig. 273 the exciting coil *EC* is shown in its original position on the hub of the machine, whilst in Fig. 274 it is supposed to be supported by some mechanically satisfactory means from the frame which supports the fixed armature coils *AA*. A glance at the two figures shows the differences there are magnetically between them. In both the exciting coil *EC* creates a magnetic flux from right to left in the space enclosed by its windings, and this flux completes its circuit by passing outwards radially in all directions, and, after passing through the armature windings, coming

radially inwards again. In this course in Fig. 273 it passes through coils *A A*, projecting downwards into the polar gap, whilst in Fig. 274 the polar gaps from iron to iron are two in each circuit, widely separated from one another, and the armature coils *A A* are carried on the laminated stationary iron close to these gaps. The total non-magnetic length in each magnetic circuit in Fig. 274 consists only of the requisite distance for the two mechanical clearances, whilst in Fig. 273 there is, in addition, the thickness of the coils *A A*. The reluctance of the magnetic circuit in Fig. 273 will therefore be greater than the reluctance of the magnetic circuit in Fig. 274. On the other hand, the exciting coil *E C* in Fig. 273 is more compact, and will not waste so much energy for the same number of ampere-turns as the exciting coil in Fig. 274.

An inductor machine of this type designed by Mr. Mordey and built by the

Brush Electrical Engineering Company, Limited, is shown in Fig. 275, which represents a machine which had an output of 100 kilowatts at 2,000 volts when running at 300 R. P. M. The magnetic circuit of the machine is shown diagrammatically in Fig. 276, in which the stationary and revolving parts are marked "stator" and "rotor" respectively. The field winding

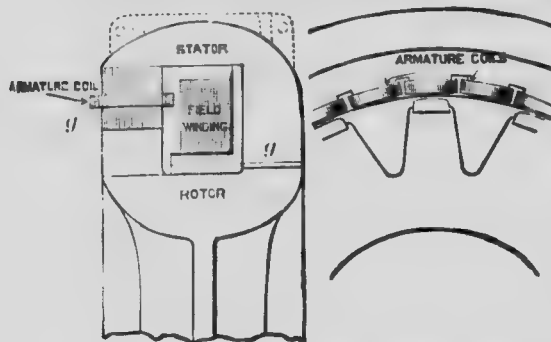


Fig. 276.—Magnetic Circuit of Mordey Inductor Alternator.

was carried by the fixed or stator part of the machine, and armature coils were only placed near one of the two magnetic gaps, *g g*, which necessarily exist in the magnetic circuit. The sectional drawing has therefore a curious one-sided appearance. The position and number of the inductors relatively to the armature coils is shown in the side view on the right. It was the same as with the polar projections and armature coils of the monocoil revolving-field type—that is, the armature coils were twice as many as the inductors. As the inductors were always of the same polarity the number of alternations per revolution in each armature coil was the same as the number of inductors, a rule different from that which obtained in multicoin machines of the ordinary type. The number of inductors in the machine shown in Fig. 275 was ten, and therefore the current produced at the given speed had a periodicity of 50 $\sim$.

The alternators were built in sizes of from 100 to 1,000 kilowatts and speeds of 300 to 100 R. P. M., but in the larger machines the pattern was modified as shown in Fig. 277, so that two armature coils were introduced

near each magnetic air gap. The modification gives a more balanced appearance to the design.

The general arrangement of field coil, armature windings and rotating poles in many inductor alternators is as shown in Fig. 278, which represents a section through these

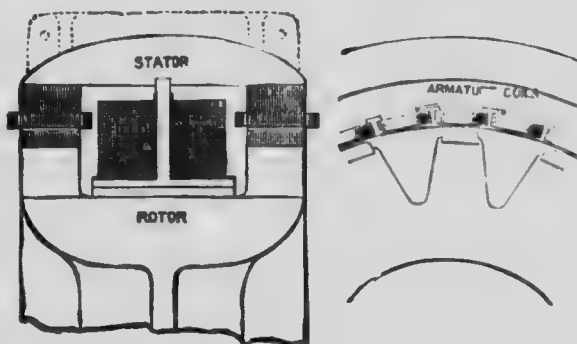


Fig. 277.—Magnetic Circuit of Larger Inductor Alternator.

parts of a 330-kilowatt machine. In this case the rotating poles were laminated to a greater depth than in the preceding example, and they were attached to a flywheel rim in much the same way as the cores of revolving field magnets. The method of clamping the armature stampings can be traced, the core being slotted at the working face to receive an ordinary three-phase winding. The exciting coil was held in its place by the connecting yoke, but it was so far separate therefrom that sometimes it was the first part of the stationary section of the machine to be

set up, the yoke and armature parts being assembled around it.

The variations in the details of these machines as designed by different manufacturers were numerous, but space will not permit their description with full particulars; nor is this necessary, as the modifications were chiefly mechanical. It will perhaps suffice to notice how the construction was modified when the machine was turned over so that the shaft became vertical, a position readily applicable, as we have already pointed out (see pages 257 and 259), for driving large machines by water turbines. Fig. 279* is a drawing half in

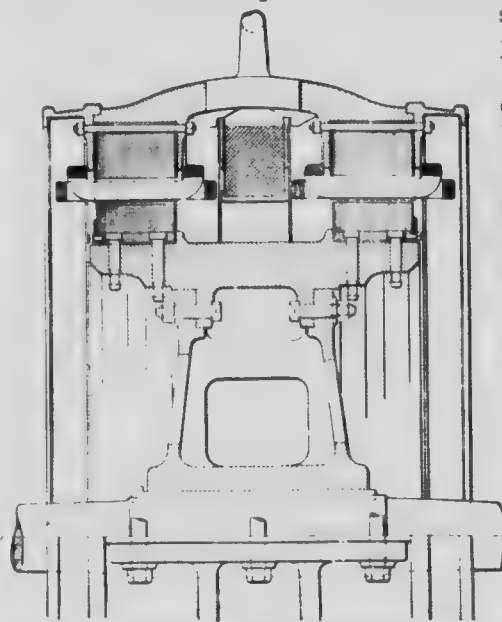


Fig. 278. Section through 330-kw. Inductor Alternator (2 1/2 full size).

* *The Electrician*, Vol. XXXVIII., page 718 (1897).

A cross-section showing, on a larger scale, the end of the inductor wheel and the armature and exciting coils is given in Fig. 280. The dynamo shaft coupled directly to the top of the turbine shaft was held in place by two bearings, one beneath the machine and the other carried by the strong cast-iron girders which spring from the tops of the columns which support the armature frame. The weight, not only of the inductor wheel, but of the shaft and the moving parts of the turbines, amounting to 55 tons, was borne by the lower of these two bearings, which was kept lubricated with oil forced into the hollow space in the bearing at a pressure of 350 lbs. per square inch. The cast-iron yoke of the fixed armature coils was in eight

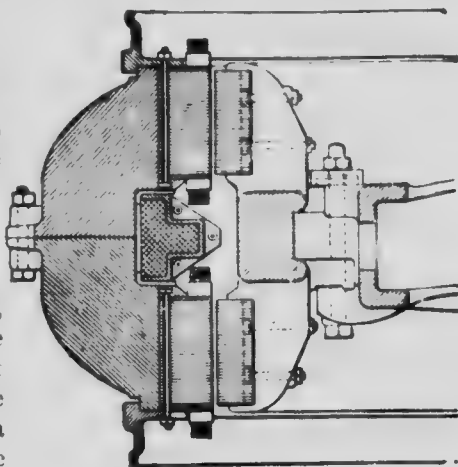


Fig. 280.—Rheinfelden Alternator, Section of Magnetic Circuit.

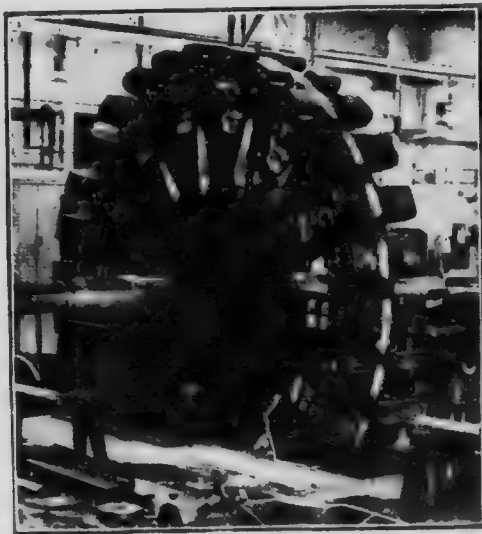


Fig. 281.—Inductor Wheel of a Large Alternator.

quadrantal sections, four for the upper part and four for the lower; these were bolted together as shown in the figures, and each quadrantal pair was supported by two columns bedded in cement. When joined up, the machine was 269 inches (22 feet 5 inches) in diameter, the outer diameter of the revolving inductor being 227 inches (18 feet 11 inches). The exciting coil was built *in situ* on each alternator casting after the latter was erected; the coil was so recessed in the fixed iron that the inductor wheel could be lifted clear out without disturbing it. The various dimensions given in Fig. 279 are in millimetres.

Each of these dynamos was designed for a three-phase output of 720 kilovolt-amperes, or 580 kilowatts, with a power factor of 0.8, at a speed of 55 R. P. M., and a periodicity of 50 ω . The pressure on

each star-connected phase was 3,900 volts, which gives a pressure, allowing for phase difference, of 6,800 volts between the line wires.

Instead of illustrating the inductor wheel of this dynamo further, we give in Fig. 281 an illustration of a vertical inductor wheel for a 750-kilowatt dynamo whilst under construction. This gives a fair idea of one of these inductors when separate from its surrounding armature and excitation coils.

Armature Details.—We pass next to the other part of the magnetic circuit, namely, that belonging to the armature, which, as already explained, consists, as a rule, of iron laminations clamped in a supporting frame or

housing. Details of the laminations, the housing, and the methods of clamping have already appeared in several of the illustrations used for explaining other details, and the reader is now referred again to these in connection with this part of the subject.

To make the information quite definite for one typical machine, Figs. 282 to 288 give dimensioned

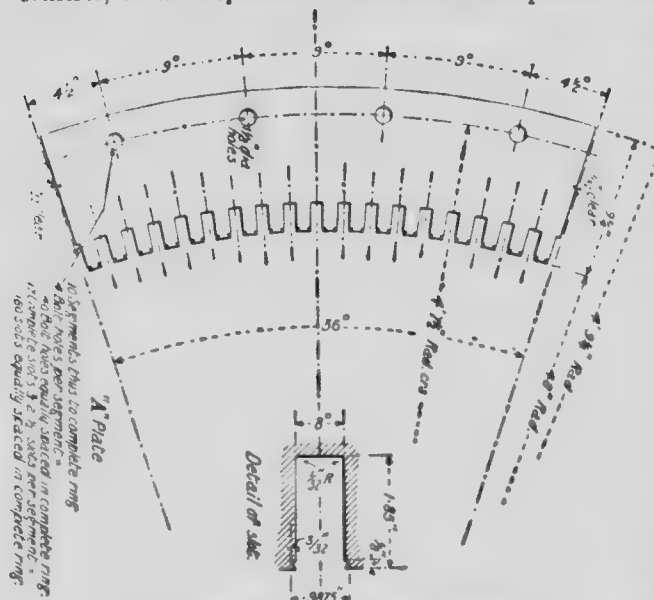


Fig. 282.—Armature Stamping of Crompton Alternator.

sketches of various parts of the magnetic circuit of the Crompton 500-kilowatt alternator (Plate V.), already partly dealt with in connection with its field magnets (see page 249). Beginning with the armature stampings, Fig. 282 shows, with all necessary dimensions, the principal stamping used in the armature. Each stamping contains seventeen slots and two half-slots, and covers a span of 36° . Ten sections will therefore complete a circle of 180 slots. The iron is $9\frac{1}{4}$ inches radially from front to back and is stamped from sheets having a thickness of 18 mils. (.018 inch). The extreme radii for the 36° are shown in the drawing, and it will be noticed that the stamping stops short of these radii with $\frac{1}{16}$ inch clearance at each end. The principal or "A" stamping, shown in Fig. 282, is, however, not the only one used, for it must be remembered that the armature ring is in two halves divided along a horizontal diameter. Now for the

same reasons which hold in regard to continuous current armatures (see page 33) it is necessary, in assembling the stampings to form the ring, to "break joint" in alternate layers, and a moment's reflection will show

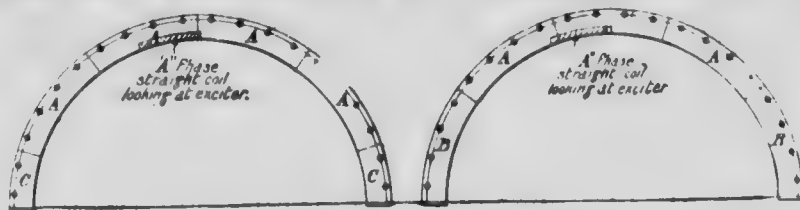


Fig. 283. Method of assembling Stampings for Armature Core.

that this cannot be done in this case with the stampings of Fig. 282. Stampings of about half the size, containing eight slots and two half-slots, and known as "C" stampings, are therefore used. These stampings, like the "A" stampings, have $\frac{1}{8}$ inch clearance on the right-hand side; but on the left-hand side they project $\frac{1}{8}$ inch beyond the median radius of the last slot or half-slot. Still another set

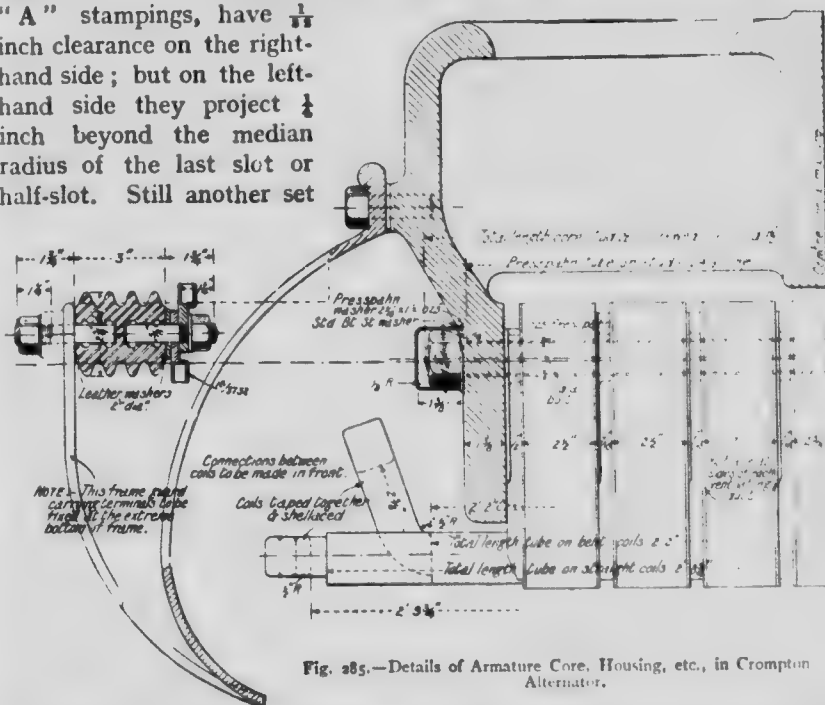


Fig. 285.—Details of Armature Core, Housing, etc., in Crompton Alternator.

of stampings, the "B" stampings, is used of the full size and pattern of the "A" stampings, except that like the "C" stampings they project $\frac{1}{8}$ inch at one end instead of having $\frac{1}{8}$ inch clearance at that end.

The use of these three sets of stampings will be understood from an

inspection of Figs. 283 and 284, which give the scheme for building up the layers of the stampings, which are to be alternately as directed by Fig. 283 and by Fig. 284. Thus a layer consisting of four "A" plates with two "C" plates at the ends, is to be followed by a layer of three "A" plates, with two "B" plates at the end; then the four "A" plates and two "C" plates again; and so on until the full thickness of 20 inches is built up. It will now be seen that the extra size of the "B" and "C" plates, which are always at the end of the semi-circular ring, is to provide the metal for machining and fitting the joint accurately, a very important matter.

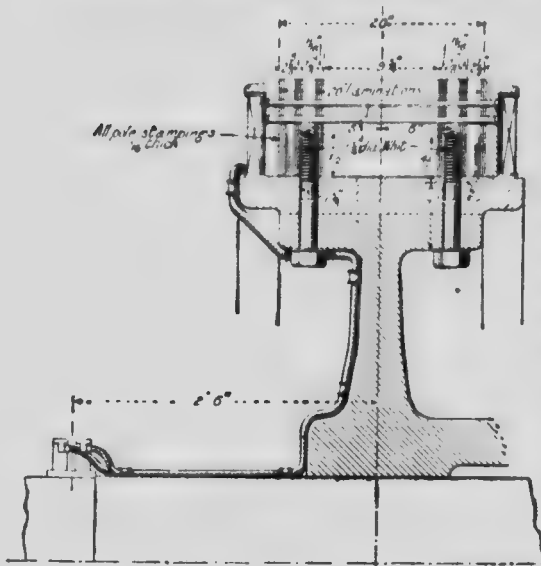


Fig. 286.—Section of Magnet Core, Rim, etc., of Crompton Alternator.

The stampings, when assembled, are clamped together in the frame as shown in the sectioned left-hand drawing on Plate V., part of which, with all the dimensions given, is reproduced in Fig. 285. It will be seen that the stampings are arranged in seven groups, each $2\frac{1}{2}$ inches thick with six ventilating ducts each $\frac{1}{8}$ inch wide between them. The over-all width of the laminations is therefore $20\frac{1}{8}$ inches; but the effective cross-section of the iron is $2\frac{1}{8}$ inches less, plus the space lost in the insulation between successive layers. These laminations are clamped to the frame in the manner shown in the drawings by one-inch studs insulated from them by tubes of presspahn 25 millimetres thick, the stud nuts clamping down on washers of presspahn of the same thickness, and being covered by mica cups $\frac{1}{8}$ inch thick. The studs are 26 inches long, and the presspahn tubes 24.5 inches. The care taken to insulate these studs from the armature iron should be noted. Other details in the drawing connected with the armature windings will be referred to in the next section.

To complete the details of the magnetic circuit of this particular machine, Figs. 286 to 288 give dimensioned sketches of the field magnet part of it: Fig. 286 is an enlarged drawing of a part of Plate V., with the dimensions added; Fig. 287 gives some further details of the field magnets as viewed at right angles to the shaft, and Fig. 288 also, in its principal drawing, gives a

view of the end plate at right angles to the shaft. The shape and dimensions of the plates which form the laminations can best be made out from Fig. 288. These laminations are 62.5 mils. ($\frac{1}{16}$ inch) thick, which is much thicker than the armature laminations (18 mils.). Their over-all thickness is 20 inches, and they are clamped together by no fewer than fourteen rivets, $\frac{5}{8}$ inch diameter, twelve of which are $21\frac{1}{2}$ inches long, and two—those which pass over the rim bolts— $23\frac{1}{2}$ inches long. There are, in addition, two bolts at the pole tips, 20 inches by $\frac{3}{4}$ inch. In Fig. 288 is also shown the space available for the magnetising coils and the method of bringing out the connection from the lowermost layer. In Fig. 286 are shown the bolts which clamp the laminated core to the rim; these bolts are $11\frac{1}{2}$ inches long by $1\frac{1}{4}$ inches in diameter, and are screwed for 4 inches of their length. In view of the thickness of the laminations ($\frac{1}{16}$ inch) the bolts are screwed directly into the built-up core without any special provision such as may be seen in the drawings of some of the other machines. The three figures will repay careful study and comparison.

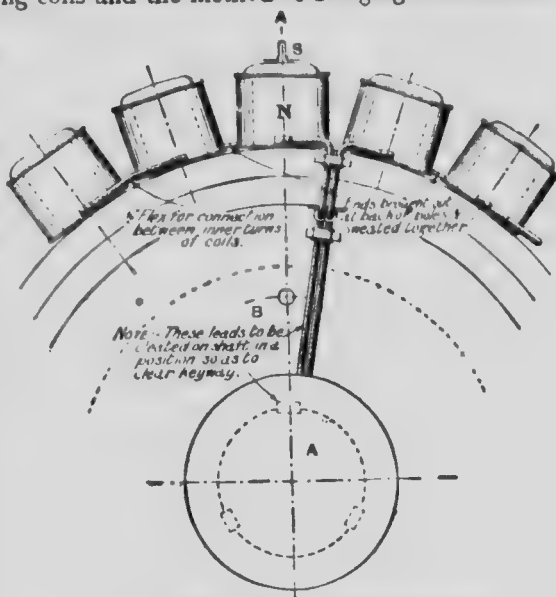


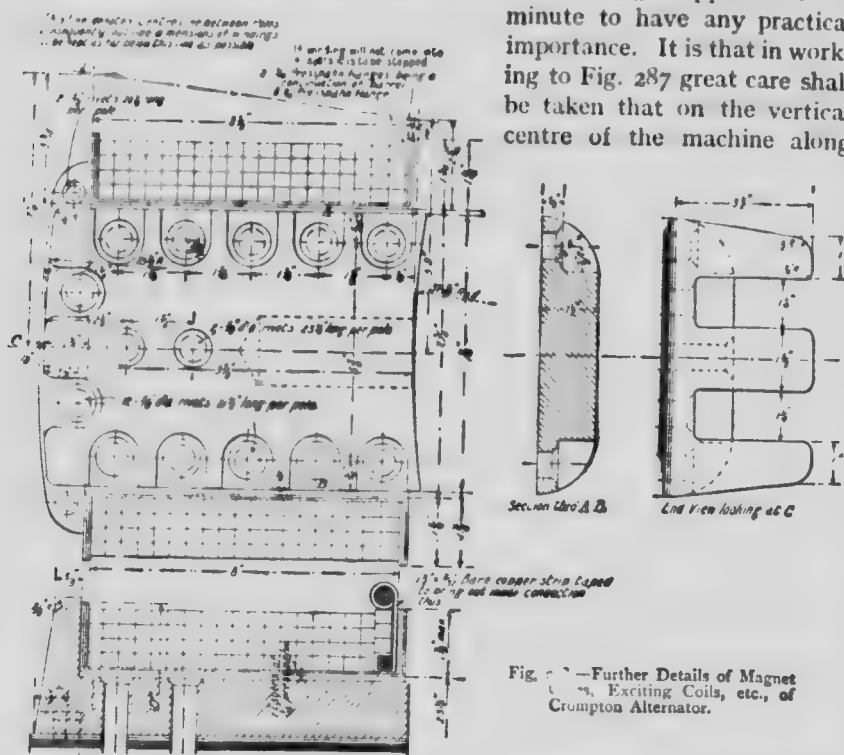
Fig. 287.—Field Magnets of Crompton Alternator.

Finally, as perhaps the most important part of the magnetic circuit, the air-gap clearance from iron to iron at the crown of the pole shoes is $\frac{7}{8}$ inch. The external diameter of the rotor is therefore only $\frac{7}{8}$ inch less than the internal diameter of the armature, which, as already mentioned, is 8 feet. It is essential, therefore, that the workmanship should be both excellent and accurate.

As we have now given full particulars of the magnetic circuit of this machine, the following data regarding the excitation circuit will be of interest. The space available for the excitation coils is clearly shown in Fig. 288. The coils are wound with four layers of wire, the conductor being 0.36 inch in diameter and insulated in the usual way, to which allusion is made elsewhere. There are 20 turns in each layer, and therefore 80 turns on each pole. The 20 coils are connected in series, which ensures that the same current shall be supplied to each. The point should be noted,

for if they were joined either in parallel or in any series-parallel combination there would be great probability, owing to small differences in resistance, that the currents in the various coils would be different, thus destroying the magnetic balance with results which might be disastrous. The coils being joined in series are at full load supplied with current at a pressure of 100 volts from the c. c. dynamos shown on the end of the shaft on Plate V.

One important instruction is given which at first sight appears far too minute to have any practical importance. It is that in working to Fig. 287 great care shall be taken that on the vertical centre of the machine along



the radial line A A, the centre of a slot *s* on the armature, the centre line of a field core *N*, one of the coupling bolts holes at *B* and a keyway on the shaft must come exactly below one another, as shown, the slot selected being that containing the outer conductors of phase *A*. The reason for this minute care is to ensure the easier synchronising of machines which are to be run in parallel and the minimising of hunting troubles, a subject which will be dealt with in due course.

Armature Stampings.—The general shape of the armature stampings which complete the magnetic circuits of other machines can, as a rule, be made out from the drawings already given, though the exact number and

Further reference will be made to details of armature stampings, slots, etc., when the subject of armature windings is under discussion (see page 296), but we give as a final example here, in Fig. 291, one of the stampings of the large slow-speed 1,000-kilowatt Brush alternator, whose field magnets have already been described and illustrated (see Figs. 251 to 254). As the inner surface of this stator has a diameter of 17 feet, as many as 30 stampings are required to complete one annular disc, and therefore each stamping which has a span of 12° only has much less curvature than any of the stampings previously illustrated. The dimensions given allow a clearance of 0.04 inch between stampings. There are two bolt-holes in each stamping for securing the built-up core to the frame. The shape of the slots is different from any previously illustrated, as the two sides are not symmetrical near the gap, the overhang being much greater on one side than

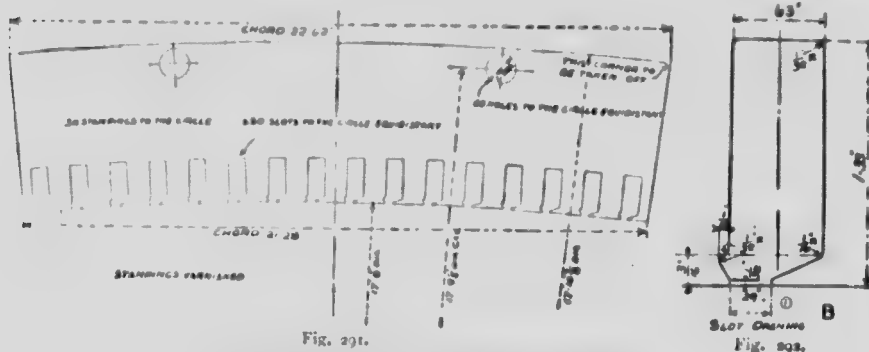


Fig. 291.
Armature Stamping for a Brush Bar-Wound Alternator.

on the other, as can be more clearly seen in Fig. 292, which is a full-size drawing of one of the slots, and may well be compared with the enlarged drawing of the slot of the Crompton alternator given in Fig. 282. The influence of this projecting iron and the consequent narrowing of the slot-gap on the magnetic flux as it sweeps over the slots should be studied.

III. —THE MAGNETIC CIRCUIT: TURBO-ALTERNATORS

The high speed of steam turbines makes them particularly suitable for producing alternate currents of the periodicity now usually employed in engineering by means of alternators with a comparatively small number of poles, and very similar to continuous current machines. At 100 R. P. M. each pair of poles, alternately N and S, will give only $1\frac{2}{3}$ periods per second. If, therefore, an armature revolving at this speed in a multipolar field is required to deliver currents at a periodicity of 40 $\sim$, the field in which it is placed must consist of 24 pairs of poles, or 48 poles alternately N and S. For higher periodicities, a cor-

respondingly greater number of poles would be required; whilst, on the other hand, if the speed be increased, the number of poles necessary for any desired periodicity can be proportionally diminished. With a prime mover, such as a steam turbine, which gives us readily speeds of 2,000 R. P. M. and upwards, it is evident that a bipolar machine will produce currents of the lower periodicities, about 40 cycles per second, now in common use, whilst a four-pole machine will be sufficient at a speed of 3,000 R. P. M. to give a periodicity of 100.

In the last edition of this book there was illustrated a four-pole 350-kilowatt Parsons turbo-alternator, with a fixed field and revolving armature, the speed being 2,760 R. P. M., and the periodicity therefore 92 Λ . More recent practice has developed in the direction of fixed armatures and revolving fields, but whichever arrangement be adopted the high speed of the rotor, as in continuous current dynamos, introduces mechanical problems the solution of which profoundly modifies the details of the design.

Dealing with rotating field magnets, the chief difficulty is to design them so that whilst providing ample ventilation for the windings, they shall be mechanically strong enough to withstand the heavy centrifugal stresses inseparable from high speeds, and also be sufficiently solid to prevent any relative movement of their component parts, which would be apt to disturb the balance which is so important in all high-speed machinery. These being the conditions, there are two chief methods of meeting them. One is by using the salient poles of the slower-speed machines, with their cores projecting from a central hub and surrounded by suitable magnetising coils. The other type is externally a smooth cylinder, presenting no projecting edges or surfaces which may stir up energy-wasting eddies of air.

Cylindric Field Magnets (Rotors).—This cylindric type has two subdivisions, in one of which the core is formed of carefully selected circular stampings of sheet steel rigidly bolted together as for an armature, and the other is machined out of a solid steel forging. The advocates of the former assert that with the stampings they obtain a more homogeneous body for their magnets, free from flaws or blow-holes, which may exist unsuspected in forgings or castings; whilst those who adopt the latter consider that any such risk is more than repaid by greater mechanical strength and less liability for any relative motion of the parts. For large machines a method intermediate between the last two is adopted. In this method, whilst a very substantial forged-steel hub is provided, the cylinder is built up to its full size with steel plates carried on the hub.

Taking, first, the full solid method of construction, which is used for machines of small output, Fig. 293 shows four different stages in the construction of such a field magnet as carried out by Messrs. Brown, Boveri and Co. In A we have the solid steel forging machined in a solid cylin-

der, ready for the subsequent operations. Next is seen the same cylinder with deep peripheral grooves cut in planes at right angles to the axis to assist the ventilation. In *c* the same cylinder has longitudinal grooves milled out parallel to the axis for the reception of the copper exciting coils. These grooves do not extend all round the periphery, but only where the copper windings are required, the central pole faces being left ungrooved for obvious reasons. Lastly, at *D*, we have the completed field magnet with the ends finished off with gun-metal caps, which help to hold the windings in their place and, entirely covering the end connections, further diminish the air friction. The slip rings for taking the current to and from the windings are placed one at either end; they are of cast steel, but are sometimes faced with copper. The conductor carrying the current to the windings is held down tightly, and no part of it is exposed; it is practically impossible for it to be displaced whilst the machine is running, however high the speed.

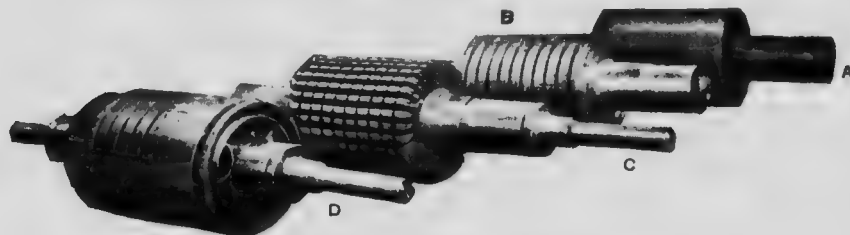


Fig. 293.—Construction of Rotors for Small Turbo-Alternators.

Fuller details of a similar field magnet, as manufactured by the Electric Construction Company, of Wolverhampton, are given in Plate VII. (Figs. 294 and 295), which gives scale drawings, partly in section, of a four-pole 2,000-K. V. A. machine, designed for 6,600 volts, with a periodicity of 50 $\sim$ at 1,500 R. P. M. In this case the solid hub is keyed and probably shrunk on to the shaft, being then grooved as shown both radially for ventilation (Fig. 294) and longitudinally for the field windings (Fig. 295), which are clearly shown in section in their places. The ventilation is still further assisted by large holes *HH*, bored nearly half-way through the solid hub from each end and parallel to the axis. There are four coils per pole, and the longitudinal slots in which they lie are not in diametral planes as in those last described, but in eccentric planes at right angles to one another for the four sets of coils. By this device the former-wound coils can be slipped into their positions without deformation. The end connections of the coils, except the outermost in each case, are also embedded in slots which lie in planes (Fig. 294) at right angles to the shaft, and parallel to the ventilating ducts. The outermost connections are held in place by gun-metal caps well screwed down. All the buried windings are held in place

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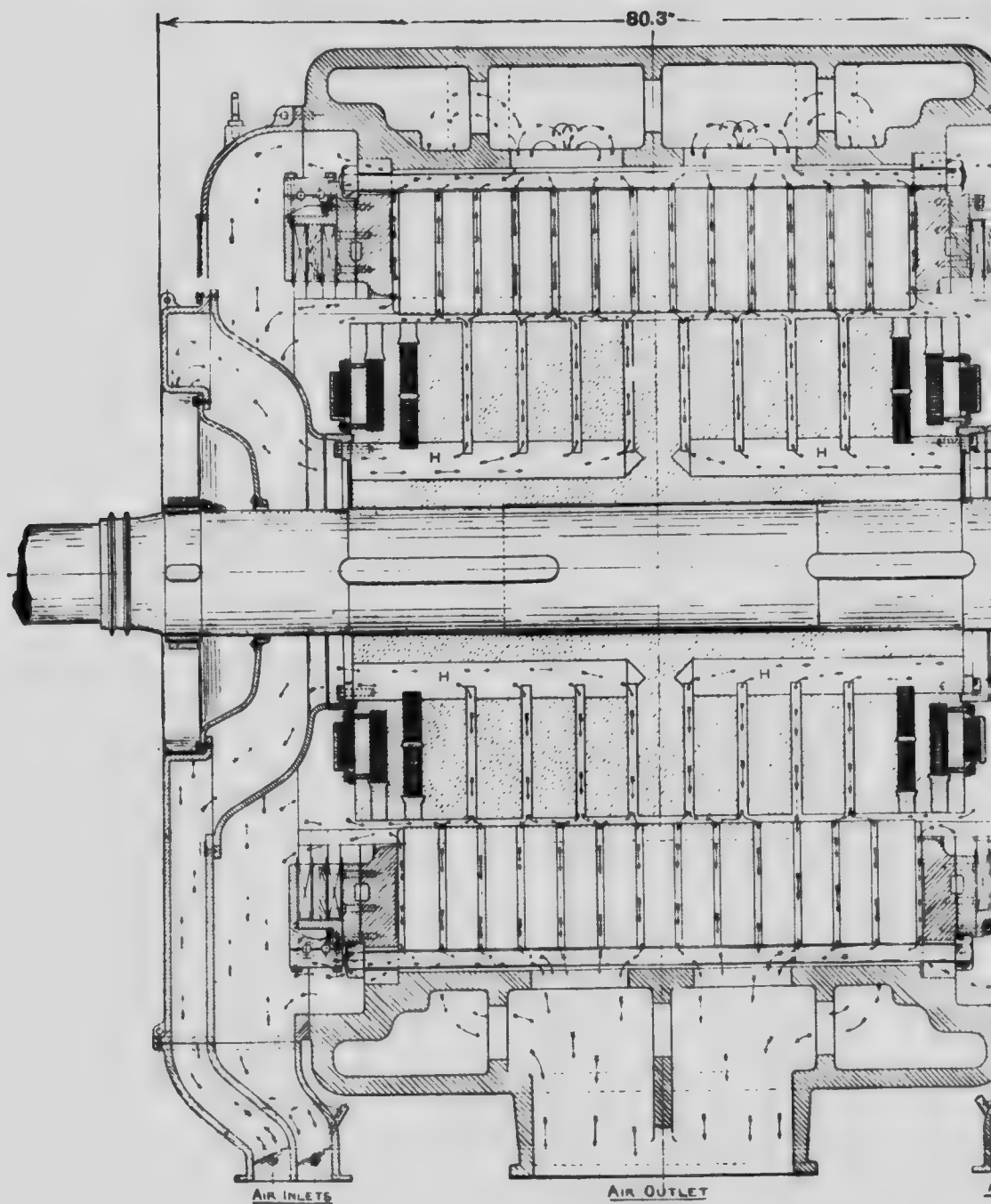
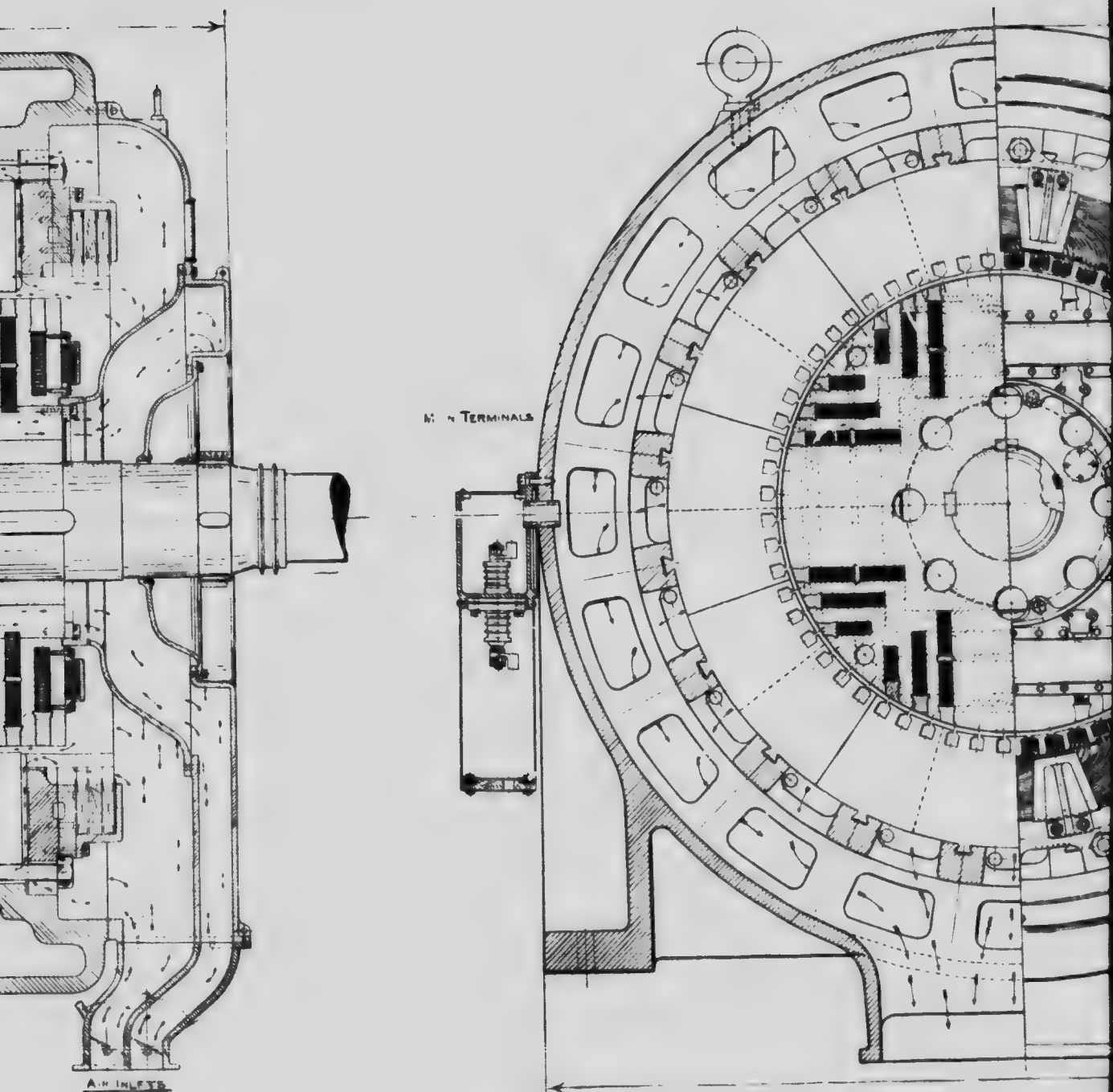
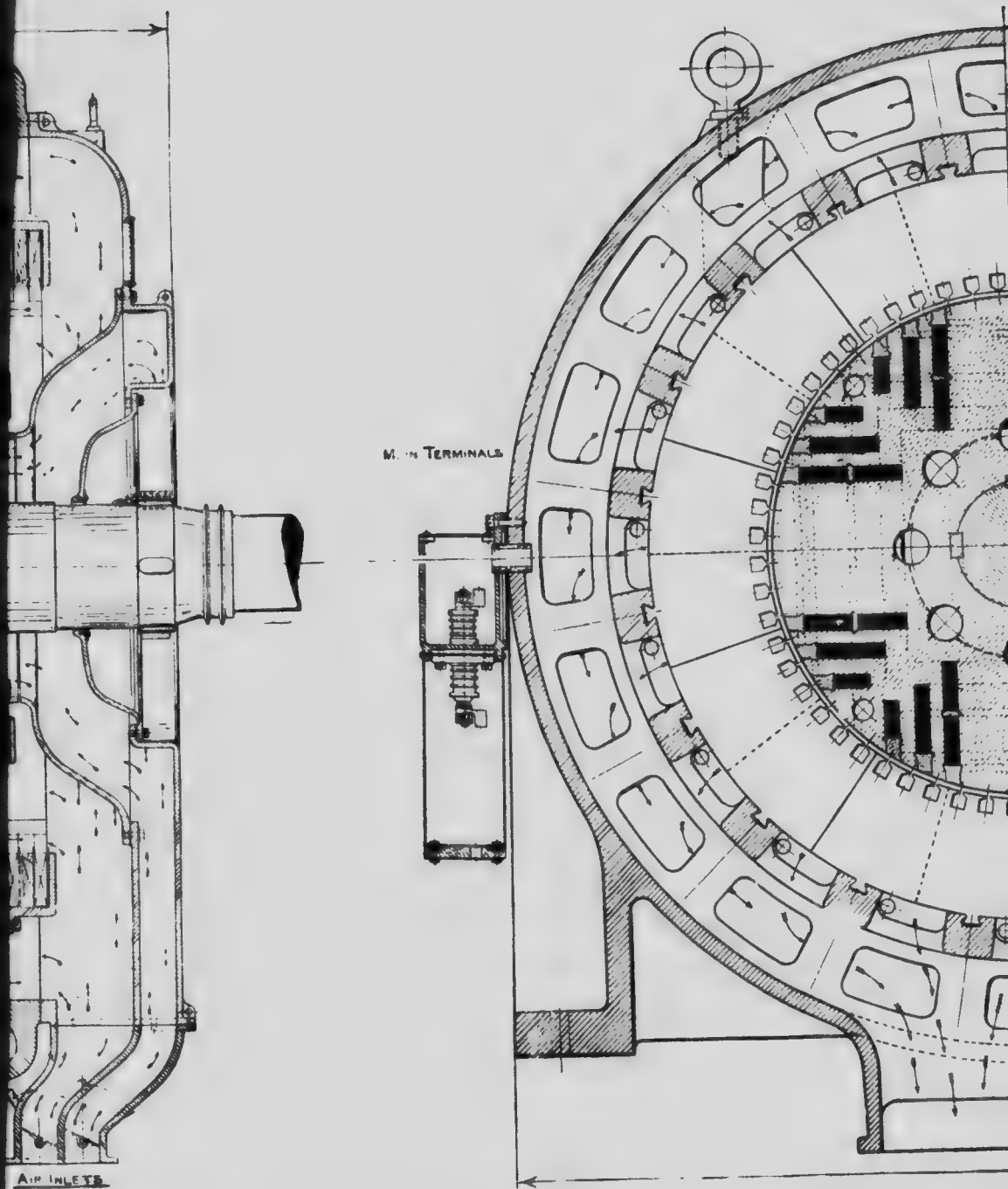


Fig. 294.



TURBO-ALTERNATOR BUILT BY THE ELECTRIC CONSTRUCTION COMPANY, 2,000 K. V. A. AT 1,500 R. P. M.



TURBO-ALTERNATOR BUILT BY THE ELECTRIC CONSTRUCTION COMPANY, 2,000 K. V. A. AT 1,500 R. P. M.

PLATE VII

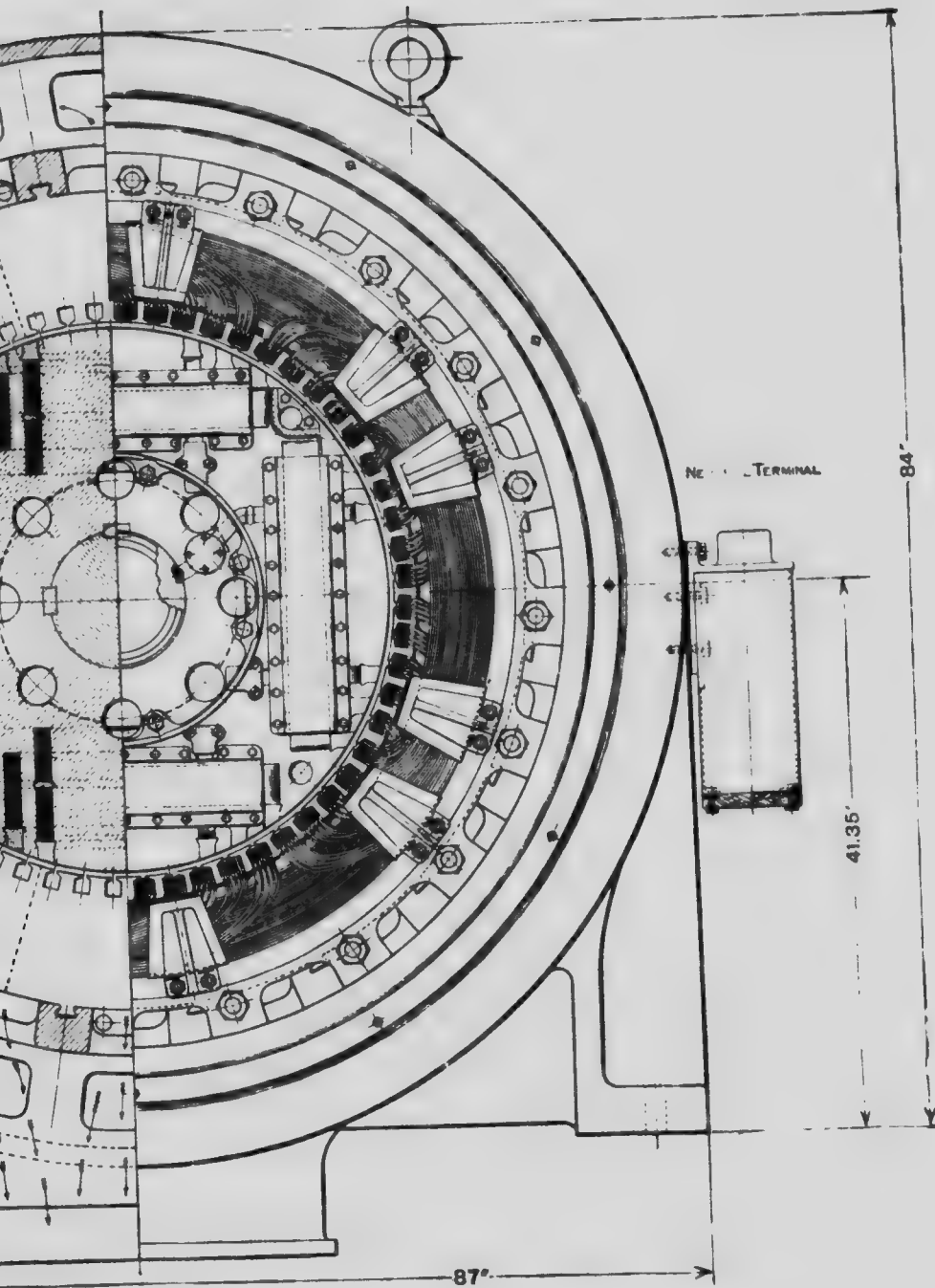


Fig. 295.



by substantial wooden wedges, which bear against undercut surfaces in the grooves which hold them against centrifugal forces.

The completed rotor, the magnetic core of which is 50.4 inches long, is shown in Fig. 296, in which the gun-metal cappings over the end windings can be clearly seen. Other details of the machine are given elsewhere (see page 295).

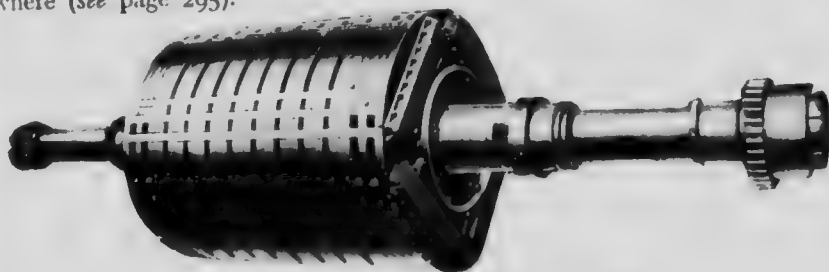


Fig. 296.—Field Magnet of E.C.C. 2,000-k. v. A. Alternator.

The method of building up the carcass of a cylindrical rotor for large machines by Brown, Boveri and Co. is shown in Fig. 297. Steel core plates are assembled on a substantial hub shrunk upon the two ends of a steel shaft, and are held in position by heavy longitudinal keys fitting into carefully machined grooves in the hub, and by heavy end plates. Radial

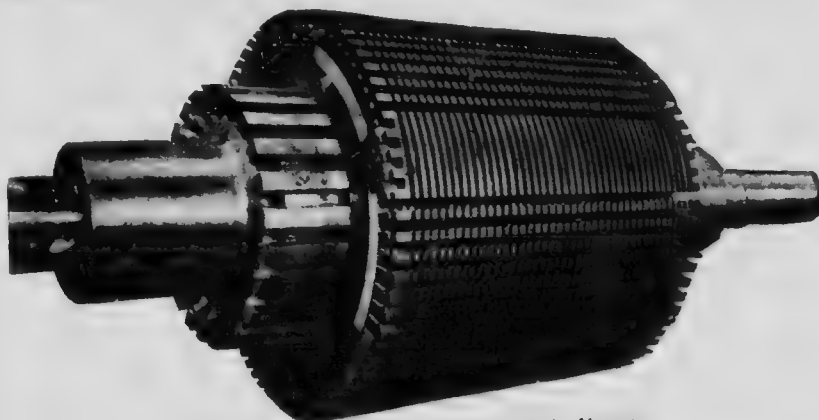


Fig. 297.—Construction of Rotor for Large Turbo-Alternators.

spaces are left between the core plates, to which air can be passed from the two ends by means of the spaces between the keys. The steel hub for a 7,500-kilowatt alternator shrunk on the shaft ends is shown in the foreground of Fig. 298, the completed armature, with its end caps of non-magnetic metal fitted on, being shown behind. On the periphery the core plates of the carcass are grooved longitudinally to receive the field windings

of rectangular copper, which are heavily insulated from the metal of the core and also from the metal wedges which are used to close the slots, the projections of which are undercut to keep the wedges in place. The

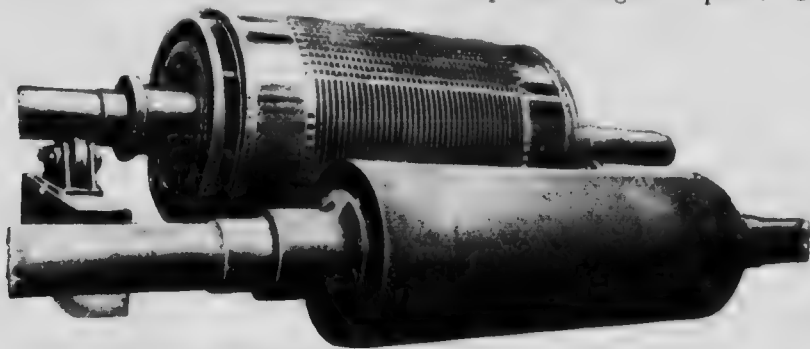


Fig. 298.—Hub and Built-up Core of 7,500-Kilowatt Brown, Boveri Alternator.

wound rotor, with the protecting end caps removed, is shown in Fig. 299, in which the details of the end connections clearly appear. In this case it will be noticed that the rotor is wound for a six-pole field. The rotor

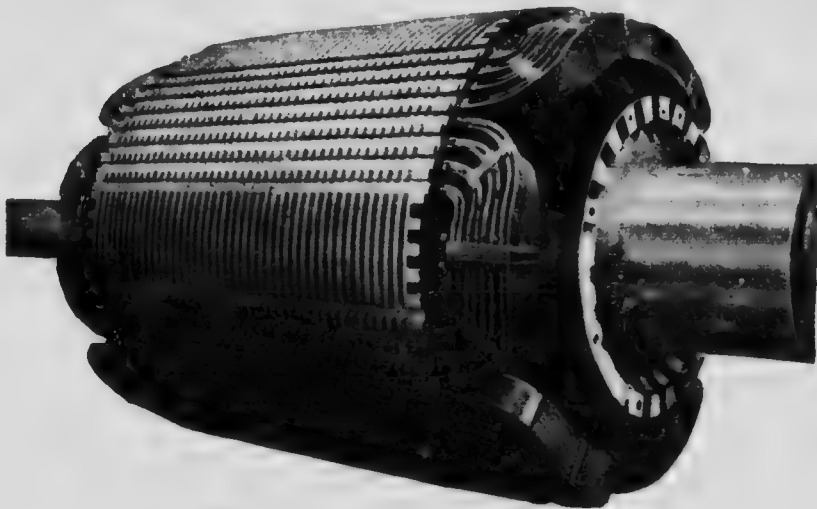


Fig. 299.—Wound Rotor for Large Turbo-Alternator with End Caps Removed.

shown in Fig. 296 for the large 7,500-kilowatt machine has four poles, intended to give 25 $\sim$ at 750 R. P. M.

The rotor field magnets designed by the British Westinghouse Electric and Manufacturing Company are of the same general type, but instead of thick core plates as in the rotors last described, they are built up of

stampings of good magnetic sheet-iron with radial ventilating ducts, formed by proper distance pieces at intervals, very closely resembling the carcass of the armature of a continuous current dynamo. The finished core of one of these rotors, ready to receive the windings, is shown in Fig.

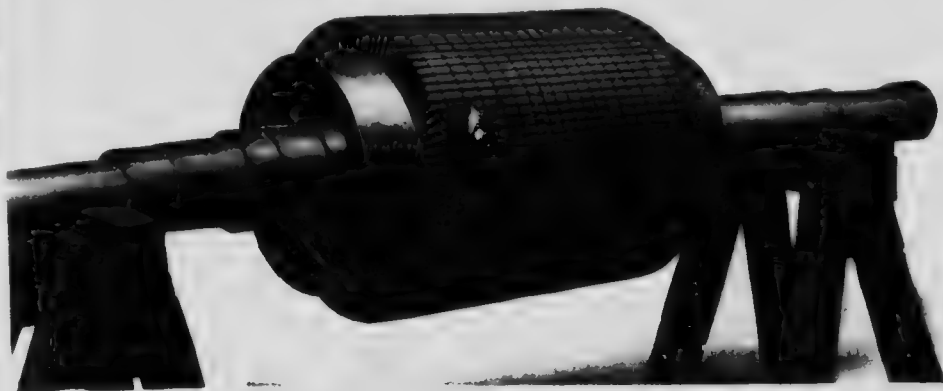


Fig. 300.—Westinghouse Field-Magnet Core for Large Turbo-Alternator.

300. It will be noticed that the longitudinal slots are radially deep and are nearly closed by the faces of the teeth. The slots are, of course, formed by the original punchings; they are evenly spaced round the periphery, but two are left unwound in the centre of each pole face. The core plates are clamped up between end plates, which, it will be seen, are pierced with a number of holes through which air can be forced behind the core plates for ventilating purposes. The method of building up such a field-magnet core is very similar to that employed for building up the armature cores of continuous current generators, which has already been described on pages 130 *et seq.* It is illustrated in Fig. 301, which should be compared with Fig. 122. The two machines of which these are the rotors may well be of much the same output, but as the rotor of the dynamo is to run at 100 R. P. M., and that of the alternator at many times this speed the core discs of the latter can be in a single stamping threaded directly on the shaft with proper guiding pins to ensure correct alignment. The holes for the ventilating ducts should be noted in Fig. 301.

As a minor variation, it may be mentioned



Fig. 301.—Building up the Field-Magnet Laminations.

that the outer surface of the field-magnet iron does not always present a true cylindric surface towards the armature, though the difference is too slight to class these rotors as forming another type. Such a rotor, as designed for a four-pole 2,500-kilowatt machine by the British Thomson-Houston Company, is depicted, partly wound, in Fig. 302. It will be

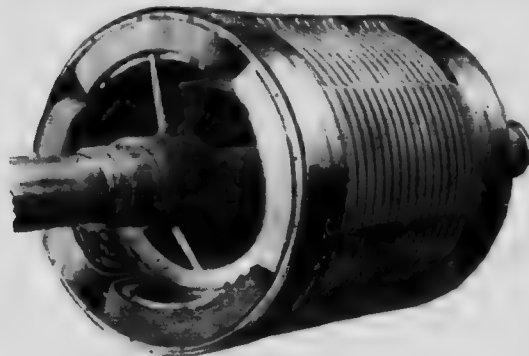


Fig. 302.—B.T. H. Field Magnet for Curtis Alternator with Pole Faces slightly projecting.

noticed that the part of the iron which is to form the pole face of the magnet projects slightly above the cylindric surface, beneath which the exciting coils lie buried, and to this extent the magnet is a salient-pole magnet. The effect of the slight variation will be to concentrate the field more definitely in the polar air gap since the reluctance of the other gaps will be con-

siderably higher. A completed rotor of the same kind, but for a machine of double the output at the same speed, is shown in Fig. 343 (*infra*). It may be noted that the rotor of the larger machine is much longer than the other.

In the above cylindric rotors attention has been drawn to the fact

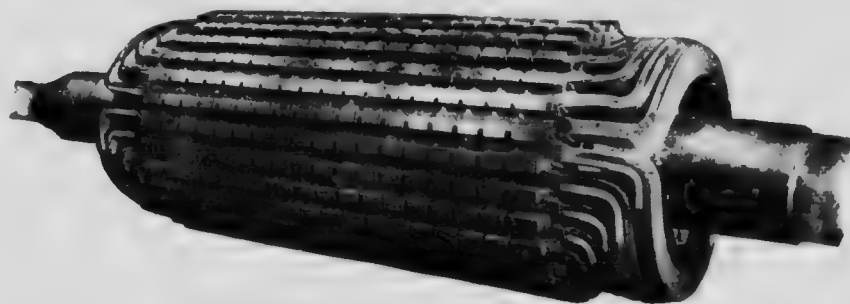


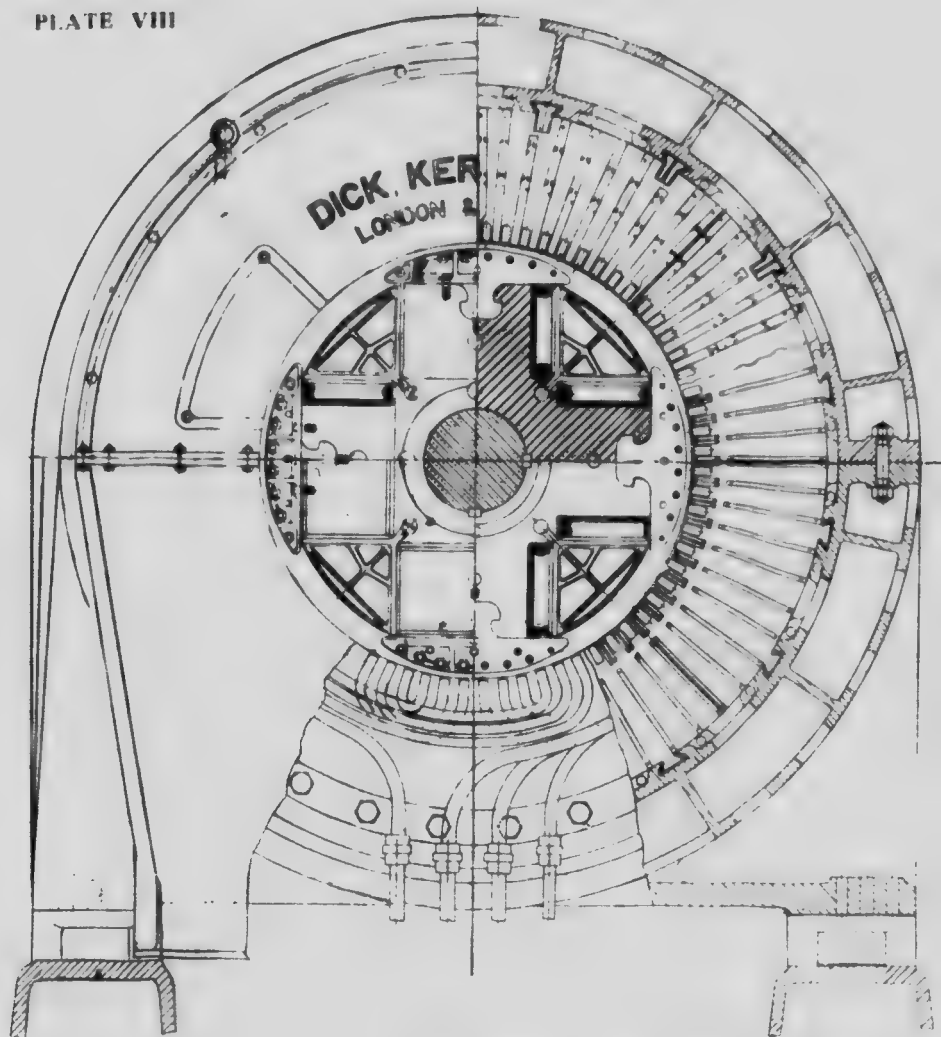
Fig. 303.—Cylindric Rotor with Distributed Windings.

that the windings do not cover the whole surface, but that polar faces are left unwound. This plan, however, is not always followed, as some designers distribute the windings over the whole face as in an induction motor. An example is given in Fig. 303, which shows the wound rotor of a 1,000-kilowatt alternator built by the Felten and Guillaume Lahmeyerwerke, of Frankfurt. The winding is obviously for a bipolar field, and as the standard frequency which is required in this case is 50 $\sim$ the

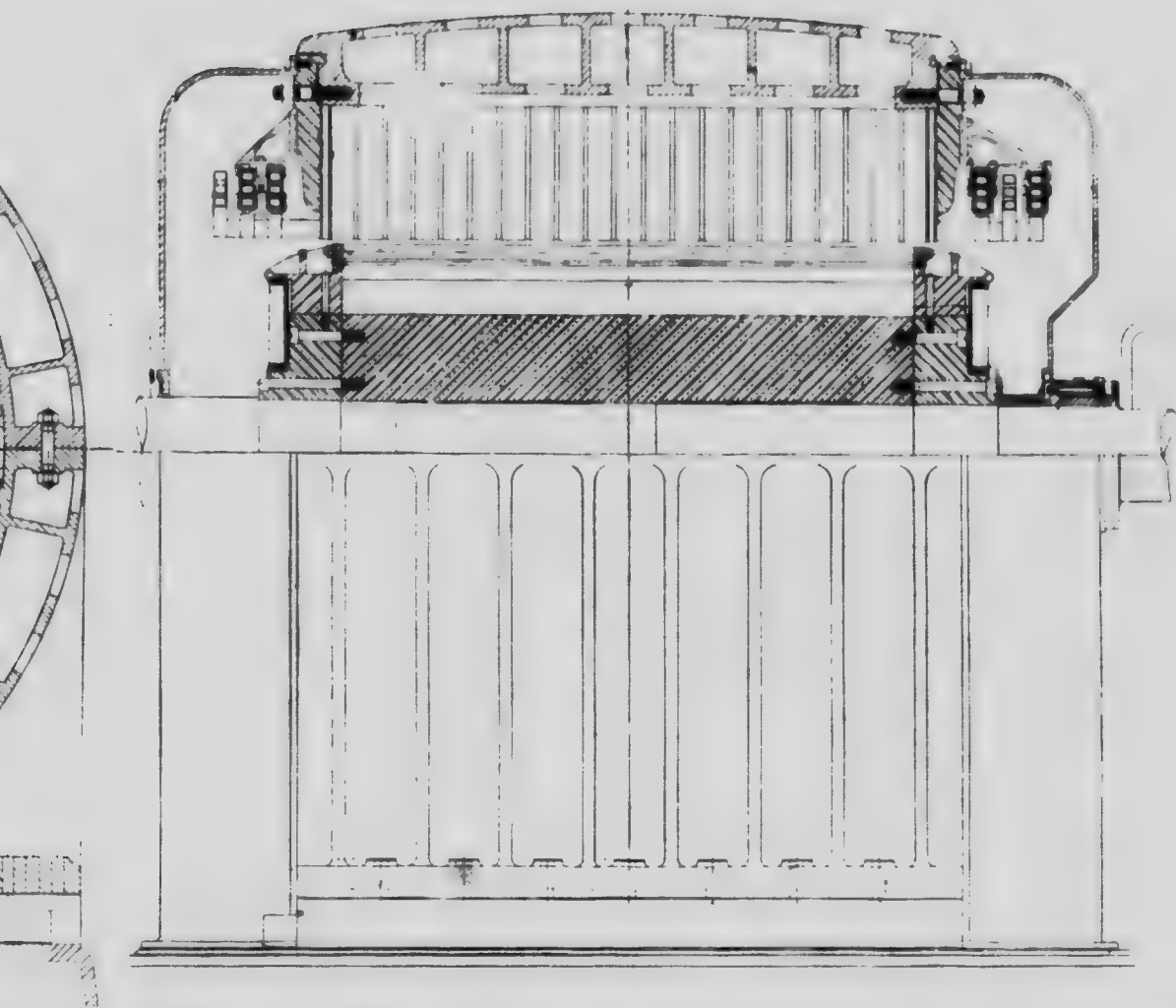
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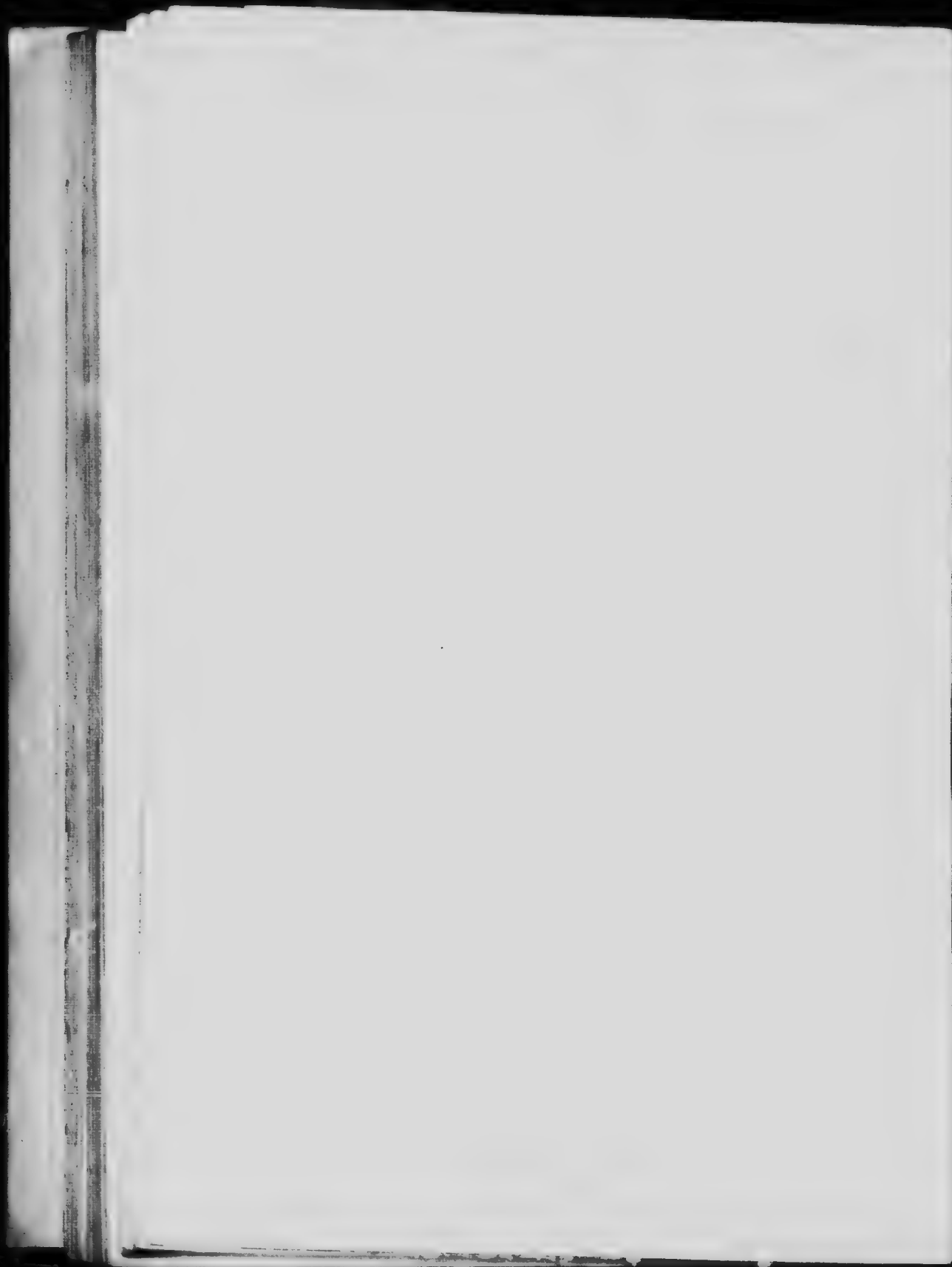
PLATE VIII



SCALE DRAWING OF THE SALIENT-POLE TYPE OF TURBINE



TYPE OF TURBINE-ALTERNATOR AS CONSTRUCTED BY MESSRS. DICK, KERR & CO., LTD.



speed of the rotor must be 3,000 R. P. M. The slots for the windings are milled out of the core, those at the extremities of the pole arcs being, however, deeper than those at their centres, so that the volume of current is greatest towards the pole tips, the intention being that the field shall be as nearly as possible sinusoidal in character. When the coils are in position the slots are closed by bronze wedges, and strong bronze caps are slipped over the end connections for reasons set forth above.

Salient-Pole Field Magnets.—The salient-pole type of field magnet as used in turbo-alternators resembles, as has been already explained, the projecting pole type used in slow-speed machines, but with some important differences in detail, especially in the precautions adopted to counteract centrifugal forces.



Fig. 204.—Dick, Kerr Salient-Pole and Cylindric Field Magnets for Turbo-Alternators

Full details of a typical machine with such poles are given in Plate VIII. The machine shown is a four-pole machine constructed by Messrs. Dick, Kerr and Co., Limited, and for a particular scale the extreme diameter of the rotating poles is 50 inches. The four projecting cores and hub are all cast in one piece, shrunk and keyed on to the driving shaft, which, to the same scale, has a diameter of 12 inches. The pole faces or shoes are laminated, being built up of stampings of sheet metal held together between massive end plates by longitudinal bolts, of which there are eight to each pole. The total length of laminated metal is 68 inches, which is less, by 5 inches, than the length of the laminated armature stampings, though the effective length of the iron will be greater in the poles than in the armature, since the former has no ventilating ducts, whilst the latter has twenty-two such spaces. The shape of the pole-face stampings should be noted, i.e. how behind the pole faces they narrow down to a neck which farther back expands into a peculiar kind of dovetail which keys into a corresponding

recess in the end of the projecting polar core. The pole stampings are also shaped to project on each side beyond the core iron, with ample margin to hold in their places the exciting coils and also the stiffening ribbed wedges which are made of non-magnetic metal. The space occupied by the exciting coils is clearly shown, as are also the details of the slip rings and their connections to the coils.

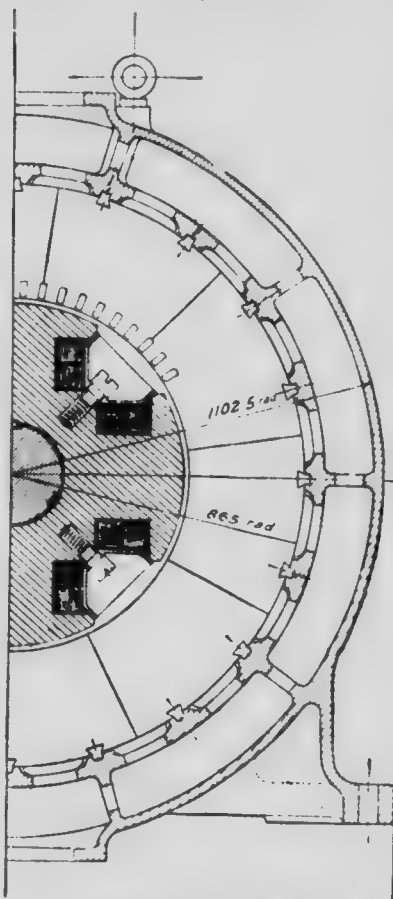


Fig. 305.—Transverse Half-Section of Salient-Pole 2,000 Kilowatt Alternator.

and the hub from which they rise, including the pole faces, are cast in one piece under pressure to ensure homogeneity and absence of blow-holes. The over-all diameter between opposite pole faces is 40 inches, the axial length of the polar iron being 53 inches. The hub is securely keyed on to the shaft, which has a diameter there of over 11 inches. The surface of the pole face is concentric with the surface of the armature

The general appearance of a rotating field built up in this way will be gathered from Fig. 304, which is a six-pole magnet built up by the same firm for a machine having the large three-phase output of 8,500 K. V. A. at 1,000 R. P. M. As a contrast, there is shown in the same photograph a cylindric type of field magnet for a two-pole machine having an output of 750 K. V. A. when running at 3,000 R. P. M. An example of a salient-pole magnet having four poles is given in Fig. 307.

Returning again to Plate VIII., it should be noted as having an important bearing on the wave form that the air gap opposite the pole face widens rapidly towards the pole tips, thus concentrating the flux in the regions opposite the central parts of the pole.

Details of a machine of the same general type are given in Figs. 305 and 306, the former being a half-section at right angles to the shaft and the latter a longitudinal half section of the upper part of the machine. The machine is designed to give an output of 2,000 kilowatts when running at 1,500 R. P. M., the periodicity of the current being therefore 50 $\sim$. The projecting poles

iron, the radial depth of the air gap being 0.59 inch (15 mm.). The exciting coils, of which there are two on each pole, are wound with bare copper strip, carefully insulated and carefully lapped on to the pole cores with a uniform tension, designed to prevent any subsequent movement

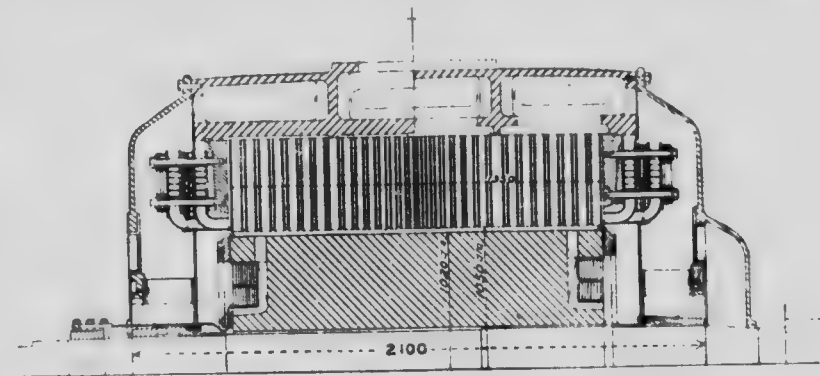


Fig. 306. Longitudinal Half-Section of Salient-Pole 2,000-Kilowatt Alternator.

of the coils. These coils are held in place by the overhanging tips of the pole faces and by heavy manganese bronze angle pieces which can be clearly seen in Fig. 305 and also in Fig. 307, which shows the finished rotor. These angle pieces are securely bolted to the main casting by nickel-steel

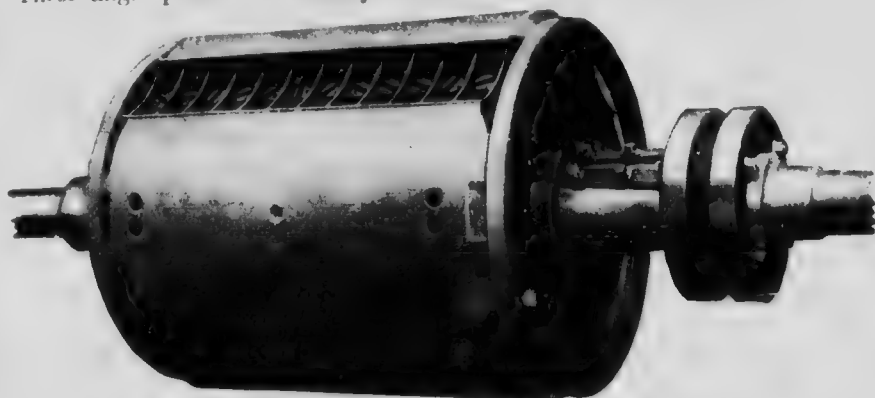


Fig. 307.—Completed Salient-Pole Field Magnet for Dick, Kerr Turbo-Alternator.

non-magnetic bolts, locked to prevent them working loose. The leads from the slip rings to the coils, and their attachment to the shaft, can also be seen in Fig. 306.

Armatures, or Stators.—So far as the armature part of the magnetic circuit is concerned, and apart from special problems connected with the conductors and ventilation, there is very little difference between turbo-

alternators and slow-speed machines. The design, of course, is much more compact, since the machines are much smaller for the same output. The greater axial length of the machines, as well as their small size, naturally modifies the design of the housing, of which there are two general types, each of which has appeared in the illustrations of complete machines already given. These two types may be described as the "open" and the "enclosed" type, the former appearing in Figs. 220 and 221 and the latter

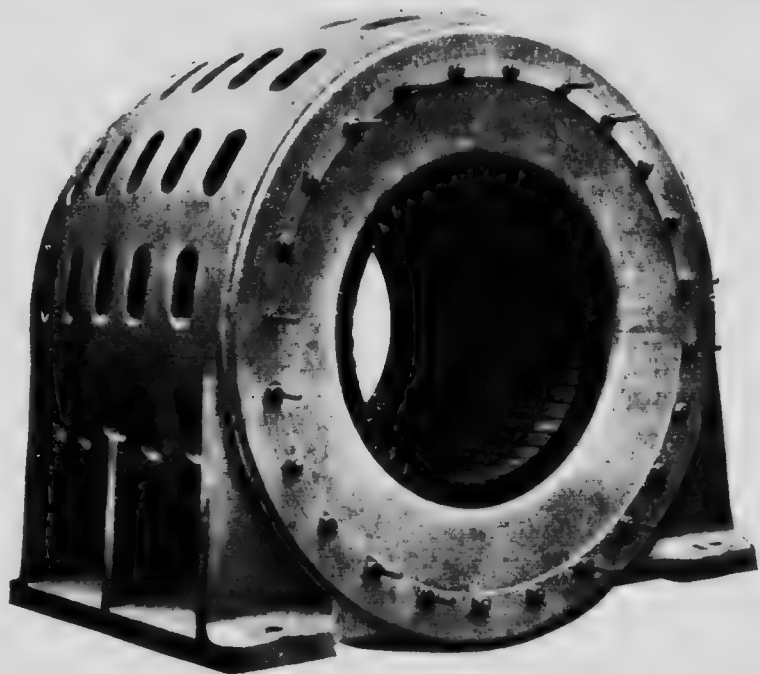


Fig. 308.—Unwound Armature, or Stator, of Dick, Kerr 1,600-Kilowatt Open-Type Turbo-Alternator.

in Figs. 219 and 225. They are, as a rule, used for the lower and the higher speeds respectively, the latter being required for the higher-speeded machines because of the greater necessity for providing efficient ventilation of the working parts. The core plates are, as a rule, radially deeper, and in view of the small number of poles, the mean length of the magnetic circuit is greater, especially where the field magnets have salient poles.

A typical stator carcass, with open type housing, for a modern turbo-alternator is shown in Fig. 308, which depicts the unwound stator of a 1,600-kilowatt alternator built by Dick, Kerr and Co. In addition to the great axial length as compared with slow-speed machines, it will be noticed that, in this case, the teeth are somewhat narrow and the slots relatively

wide, the latter being nearly closed on the inner periphery facing the revolving field. The complete machine, of which this is the stator, has already been illustrated in Fig. 221, and additional particulars will be found on page 229.

Details, drawn to scale, of the stator part of the magnetic circuit of a modern turbo-alternator of the enclosed type, built by the Electric Construction Company, the rotor of which has been already described, have been given in Plate VII., which shows both a longitudinal and transverse section of the machine. Each core plate, ten of which make a complete ring, carries two dovetails, which key into projections from the housing. As is usual, the plates are staggered in successive layers. The laminations occupy an axial length of 42 inches, in which there are no fewer than fourteen ventilating ducts; they are clamped together between massive end rings by heavy longitudinal bolts. The inner surface of the assembled core plates is 42 inches in diameter, the

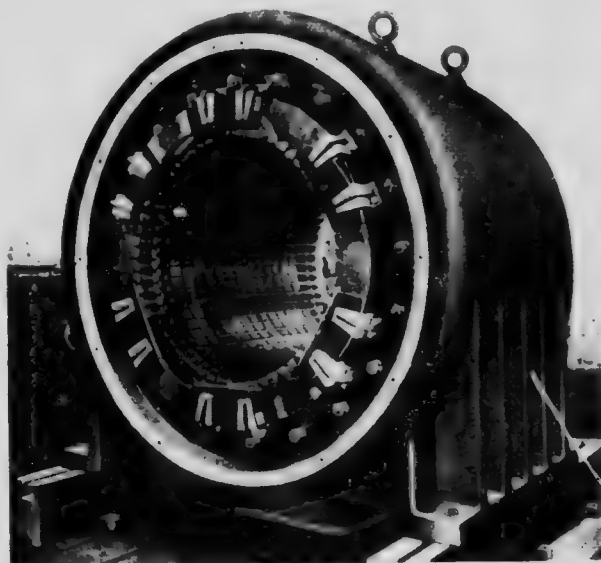


Fig. 309.—Wound Armature of E.C.C. Enclosed-Type 2,000-K. V. A. Alternator.

radial depth of the plates being 10 inches. There are fifteen slots per pole, which for three-phase winding will give five slots per pole per phase. From these data the approximate mean length of the magnetic path in the armature iron can be deduced. The output and other details of the machine are given on page 286, and the complete stator, which has a housing of the enclosed type, is shown in Fig. 309, to which further reference will be made later.

Details of the armature part of the magnetic circuit of a salient-pole turbo-alternator, already referred to on page 291, will be found in Plate VIII., in which can be clearly seen the details of the armature stampings and the shape and size of the slots, which are nearly, but not quite, closed. The stampings have a radial depth of 16 inches, and dovetail into the housing, which is cast in two parts, divided along the horizontal

diameter. The slots are 2 inches deep and 1 inch wide, the teeth being slightly thicker. There are seventy-two slots in all, which, as the winding is three-phase, gives six slots per pole per phase. In the lower part of the left-hand figure are shown the terminals, four in number, for the three ends of the star winding and the neutral wire respectively.

IV.—THE ARMATURE WINDINGS

It has already been pointed out that the armatures of alternators are far more varied than those of continuous current machines. The latter, in the majority of cases, are closed-coil armatures of the drum- or ring-wound types, and though there are important exceptions they are not numerous. On the other hand, although we find both ring- and drum-wound closed-coil armatures used on alternators, there are machines in which totally different systems, usually of the open-coil type, are employed. In the former the windings may be regarded as fairly uniformly "distributed" round the periphery of the armature, whilst in the latter they are often more or less "bunched" together or "collected" at special regions of this periphery, the other regions containing no active conductors. In addition, a distinction must be drawn between those types of armatures which can be wound for single or polyphase currents and those which can only be used for single-phase windings. As a rule, the "distributed" windings can be wound for one or any number of phases, whilst the "bunched" windings are usually available for the generation of single-phase currents only. Lastly, the armature may be either fixed or rotating.

It will therefore be convenient to adopt the following classification:—

(1) *Ring-wound armatures.*

- (i.) Windings (a) distributed uniformly for either single or polyphase currents;
- (b) bunched together for single-phase currents only.

- (ii.) Cores (a) smooth;
- (b) slotted or tunnelled.

(2) *Drum-wound armatures.*

Windings and cores as in class (1).

(3) *Disc armatures.*

Windings (a) In flat coils with or without iron cores, usually generating single-phase currents;

- (b) In short solenoids with iron cores for single or two-phase currents.

(4) *Pole armatures* for single-phase currents.

Any of these armatures may be fixed or rotating, and, as a matter of fact, well-known machines have been built of each kind in all the above classes, but the great majority of modern machines falls into class (2).

Examples have already been given in the last section of several modern armatures which belong to one or other of these classes; in what follows we shall adhere to the above classification.

(1) **Ring-Wound Armatures.**—It has already been shown (see page 635, Vol. I.) in connection with rotary converters that an ordinary closed circuit Gramme ring in a bipolar or a multipolar field can be used to generate alternate currents by the simple device of replacing the commutator by two or more slip rings joined to appropriate points in the windings. The E. M. F.'s generated, however, in these simple cases will not be high, since the maximum E. M. F. attainable is limited by the maximum inductive action possible in the windings between any two points successively connected to the slip rings.

To obtain high E. M. F.'s it is necessary to modify the winding by reversing it at points which are separated from one another by a space equal to the pole pitch, so that the inductions in successive groups of these windings may all be in the same direction in the armature circuit at the same time. For

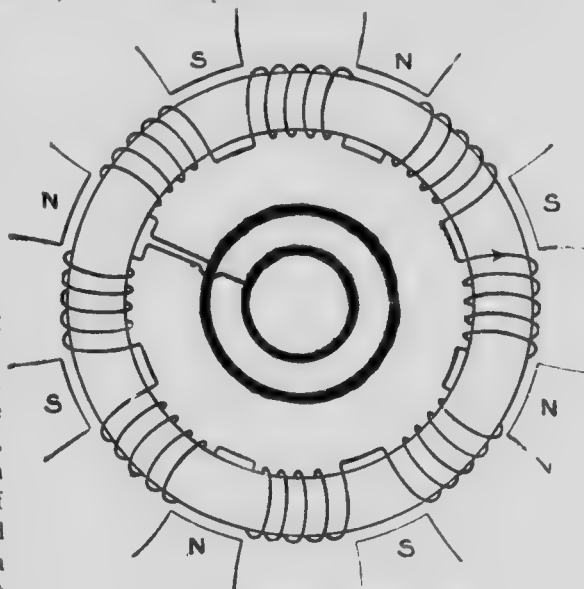


Fig. 310.—Ring Windings for High Voltage.

the highest E. M. F. in a given case for single-phase currents the closed winding should then be cut at one of the reversing points, and the two ends taken to the slip rings for connection to the outer circuit, as shown diagrammatically in Fig. 310. Lower E. M. F.'s can be obtained by closing the winding and connecting appropriate points to the slip rings. In this case different parts of the armature will be electrically in parallel. The windings can either be uniformly distributed as in an ordinary Gramme ring (the reversals being made at proper intervals, or they may be bunched together as in Fig. 310, leaving parts of the core unwound. The evenly distributed winding gives trouble owing to reactions with lagging currents and otherwise, and therefore the bunched winding is usually adopted for single-phase currents. A machine of Kapp's so wound was described in the last edition of this book. The

disadvantage of this method is that valuable space on the core is not utilised, but, as will be seen when dealing with drum windings, an additional circuit or circuits having a different phase or phases can be wound on the empty sections and the full available space utilised. This was actually done in one of Gramme's early alternators already described (Fig. 534, page 556, Vol. I.), which was ring-wound with four circuits,

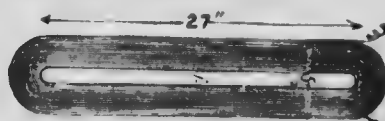


Fig. 311.—Early Type of Coil of Drum-Wound Armature.

the separate coils of which were so distributed round the ring that they covered its whole surface, and in each circuit the individual coils were spaced at a mean distance apart equal to the pole pitch, as in Fig. 310. In

most modern alternators drum windings are adopted, and these will now be considered.

(2) **Drum-Wound Armatures.**—One of the earliest forms of alternators which was widely used had flat coils laid upon a smooth iron core, and therefore was essentially a drum-wound machine. The coils in this, the early form of Westinghouse alternator, were constructed, as shown in



Fig. 312.—Armature of Early Form of Westinghouse Alternator.

Fig. 311, of conductors wound in a long flat spiral. These were placed upon a smooth-core armature carcass somewhat shorter than the longitudinal space in the middle of the spiral, and were held in their places by binding wires, as shown in Fig. 312, the curved ends being turned over at right angles and clamped underneath the substantial end plates, which can be clearly made out in the figure. The centres of the coils were placed at a distance apart equal to the pole pitch, and the outer conductors of neighbouring coils were alongside one another. Electrically the connections were similar to those shown in Fig. 310 for a ring winding, and

therefore the induced E. M. F.'s at the moment of maximum induction were all in series. The two ends of the windings were brought to the slip rings shown in Fig. 312.

The amount of space lost on the surface of the armature by the narrow gap in the middle of these coils was not a very large fraction of the whole; but then these machines were chiefly used to supply current to glow-lamp circuits of low inductance, in which the power factor was high and the lag of the current consequently small. With the increase in the size of the machines, and with the greater variety in the loads to be provided for, modifications became necessary.

The principal modifications will be understood by comparing Figs. 311 and 312 with Fig. 313, which represents an armature of a more modern Westinghouse single-phase alternator having an output of 250 kilowatts. In Fig. 313 the coils are still wound, as in the earlier machines, before being placed on the core; but as the latter is now slotted instead of being smooth, each complete coil is



Fig. 313.—Westinghouse 250-k. w. Single Phase Alternator Armature.

grouped in five sections of one or more turns each, so as to occupy when in place ten of the slots of the uniformly slotted core. The central space of the innermost turns has been widened until it now embraces three of the slots which are left empty; and, therefore, three parts out of 13, or 23 per cent. of the whole available winding space of the armature, is left unoccupied. The connections from group to group are alternately between inner coil and inner coil and between outer coil and outer coil. The former connections are clearly visible in the figure in the shape of links carefully clamped to an inner ring; the other con-

nections, being between adjacent slots, are quite short, and are readily made without special devices being necessary. The point at which the continuous connection of adjacent coils is interrupted and the connection made to the slip rings is at the lower part of the figure, where one of the long intercoil connectors is omitted and its place taken by two radial conductors which eventually reach the rings by paths almost diametrically opposite one another, thus ensuring good insulation.

An important difference between the earlier and later forms of armature

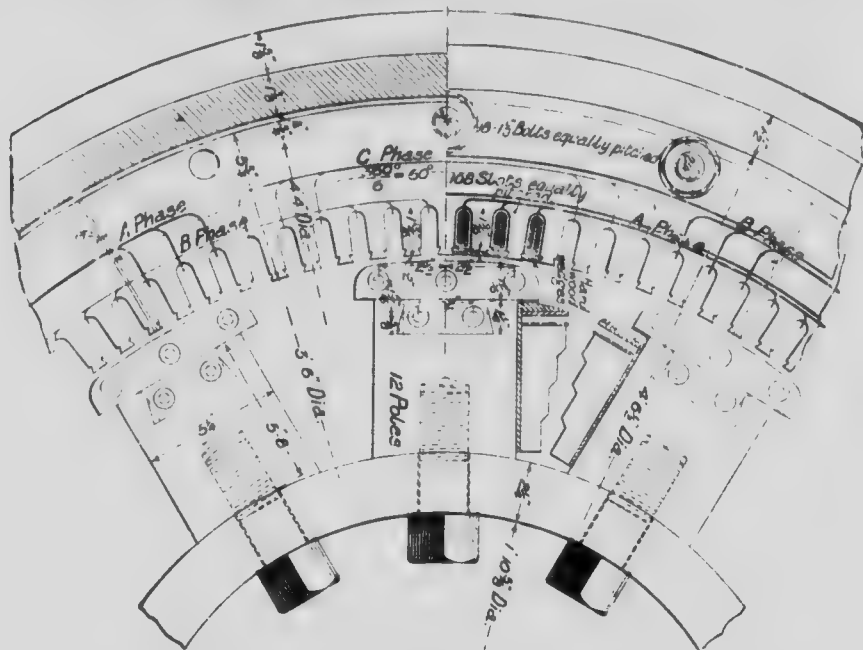


Fig. 314—Details of Armature and Magnets of a Three Phase Alternator.

is in the matter of ventilation. In Fig. 312 there is practically no special provision made for keeping the conductors and the core cool by driving cold air through the latter, but in Fig. 313 the core is built up exactly like the core of a modern continuous current armature, and with the same arrangements for ventilation which have already been described (see page 132).

Polyphase Windings.—As already mentioned, the space lost in single-phase machines can be fully utilised by winding therein another phase or phases. When this is done, however, the space devoted to each phase is less than that given in a single-phase machine, which, as we have seen above, may amount to 77 per cent. of the whole. Obviously, when there are more phases than one, the space should be equally divided between the phases,

and, therefore, in two-phase machines half the slots, and in three-phase machines one-third of the slots, must be given to each phase. This offers no difficulty, as in each case the space per phase is less than can be occupied

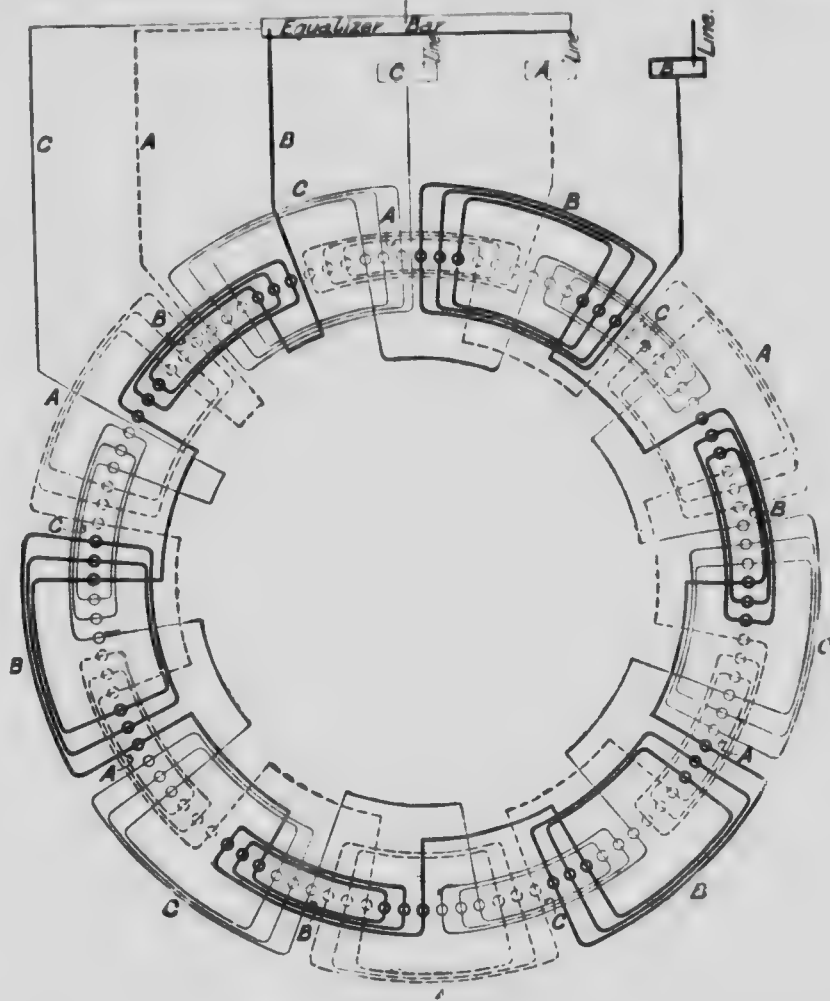


Fig. 315.—Diagram of Three phase Winding for a 12-Pole Alternator

without inconvenience by a single phase. It further follows that the number of slots per pole must be a multiple of two for two-phase and a multiple of three for three-phase windings; thus the 13 slots per pole of Fig. 313 could not be used for any ordinary polyphase windings.

Some of the details of a three-phase winding evenly distributed round

the fixed armature of a 12-pole machine are given in Fig. 314, in which the armature core has nine slots per pole or three slots per phase per pole. The slots per phase for each pair of poles were wound with 24 active conductors, each consisting of copper wire 128 mils. in diameter covered with 143 mils. with insulation. There were, therefore, 528 active conductors in each phase, the average E. M. F. in each conductor being from 5 to 6 volts, since the whole machine gave from 2,850 to 3,100 volts per phase. The plan of the winding is more clearly shown diagrammatically in Fig.

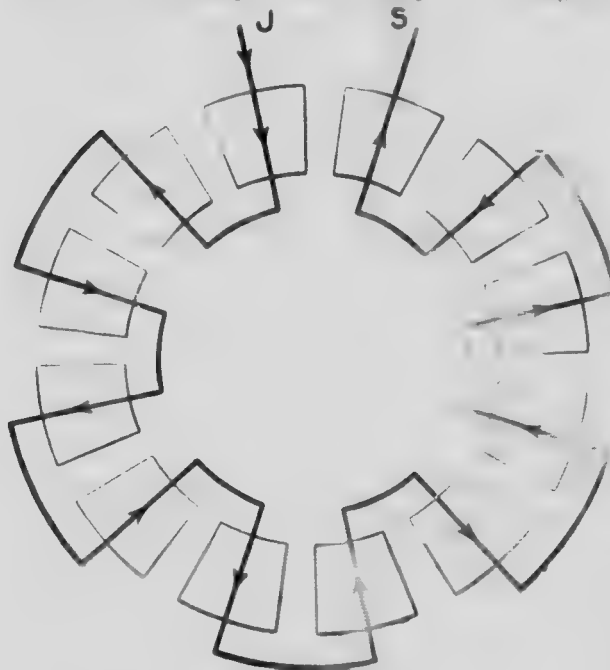


Fig. 314.—Multipolar Winding, One Phase.

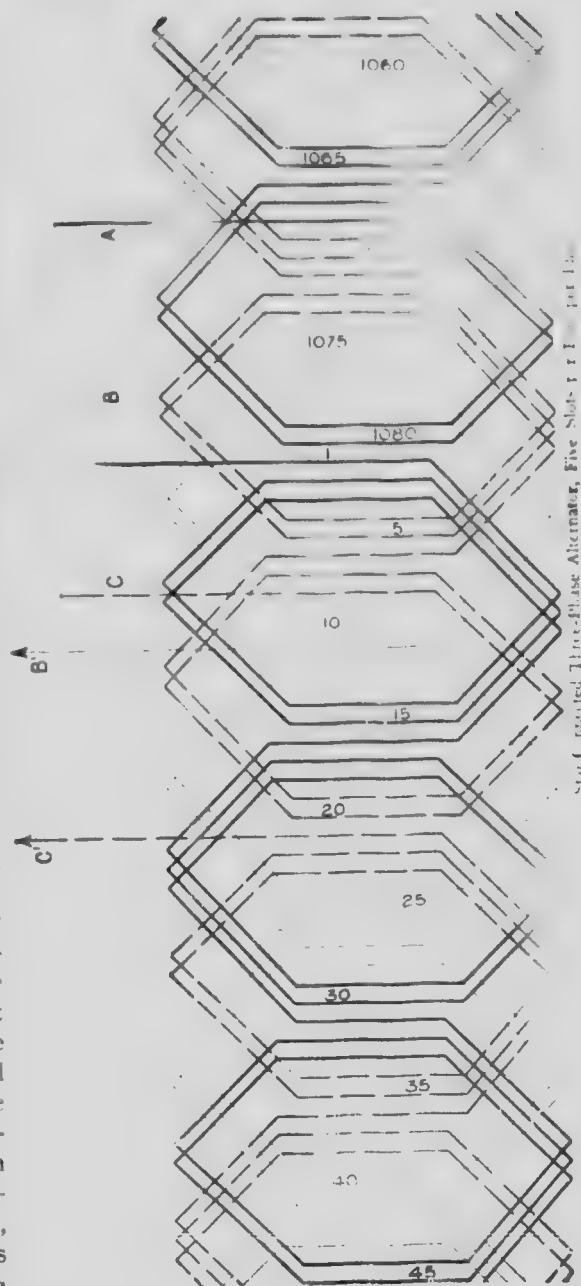
the pole pitch, as in single-pole winding. Then the successive groups of the "A" phase instead of being placed side one another, are separated by a distance equal to the pole pitch. In this way space is found for the windings of the "B" and "C" phases, which are shown with thick and thin lines respectively.

The general plan of such a winding is perhaps even better shown in Fig. 316, in which the simplest possible case is taken—namely, one conductor in one slot per phase per pole. The connections between successive conductors being made alternately at the inner and outer ends alternately, the induced E. M. F. is in series throughout the windings, and will give the same value at any two points *s* and *j* connected to the slip ring and the

The winding is a star connection (see page 549, Vol. I). It can be readily traced starting from the "common neutral" point, the "neutral bar" of the machine. Thus the "A" winding, shown by a dotted line, consists of six groups of coils, one group for each pair of poles. In each group the active conductors on one side are at an average distance from the active conductors on the other side equal to the pole pitch, instead of the whole of the conductors being within the space of

junction point respectively. The other phases to be similarly developed and the connection made as in Fig. 315. The winding is three phase. The additions required where there are more conductors and slots per phase per pole can be readily made out by comparing the figures.

As a further example, Fig. 317 gives both the beginning and the ending of the developed plan of the winding of a 72-pole machine of the Electrical Company, Ltd., of London. In this machine, designed for a three-phase output of 3,000 kilovolt amperes, with 6,000 volts between the line wires, there were 1,080 slots, or 15 slots per pole. The windings were star connected for three-phase currents, the common junction point being at J; there were therefore five slots and conductors per phase per pole. In the diagram setting out from the outer slip-ring terminals A', B', and C', the first 45 conductors are shown starting



Star Connected Three-Phase Alternator, Five Slots per Pole per Phase

from No. "1" in the "A" winding, and counting from right to left. The last 23, finishing with No. "1,080," also in the "A" winding, appear at the right-hand side, also numbered from right to left. The intermediate conductors follow the same plan. This diagram should be carefully compared with the preceding to ascertain the modification introduced by the increase of conductors per pole per phase from one to five.

Standard armature stampings have been already illustrated in the preceding section (see pages 278 to 284). Where "former-wound" coils are used the slots are usually quite open, with straight sides, but often dovetailed at the top for the keying of the wooden wedges which are so fre-

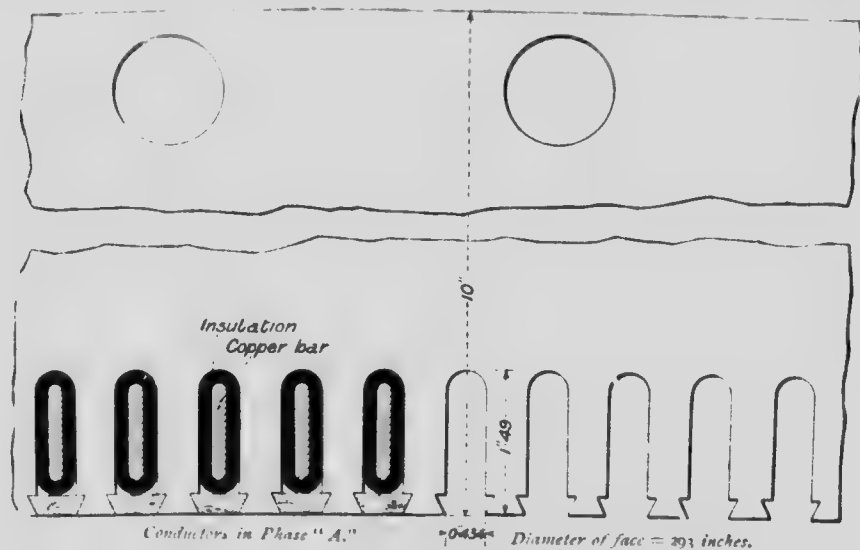


Fig. 318.—Part of an Armature Stamping showing Conductors in Position

quently employed to hold the windings in their place. Where the voltage is sufficiently low for "bar" windings, the slots are sometimes closed over either nearly or completely, thus killing the eddy currents in the thick copper of the winding.

Part of one of the armature stampings for the alternator, the scheme of whose winding has just been described above, is shown in Fig. 318, in which there appear ten slots, five empty and five containing the conductors of one phase properly insulated and held in their places by wooden wedges. The inner face of the armature iron has a diameter of 29.3 inches (24 feet 5 inches), and the laminated stampings are 10 inches deep from this face. As the poles rotate with an angular velocity of 83 R. P. M., the average peripheral speed with which the field flux sweeps over the face of the armature is 6,400 feet, or over a mile, per minute. The

mechanical clearance between the fixed and moving iron is only 9 millimetres, or 0.357 of an inch, and therefore both the flywheel on which the field poles are mounted and the frame which supports the armature iron must be very carefully designed so as to have the requisite mechanical rigidity to maintain this small clearance intact under the severe conditions of actual work.

When, as is necessary for high-voltage machines, the separate armature coils have many turns, they are usually wound on formers, and a great deal of attention and care is devoted to the details of shaping and insulating. For instance, Messrs. Dick, Kerr and Co., after forming the coils absolutely to the designed size and shape, on special machines, pass them through a heavy insulating compound which completely fills the spaces between the already cotton-covered conductors. Next, the coils are compressed in special hot formers, and the final outside insulation, composed of a fibrous compound for low-voltage machines

or of mica in continuous layers for high-voltage machines, is then sewed over the coil, which is well baked several times at different stages of the process. The coils are finally tested severely for insulation before being placed on the machine, and in sliding the coils into the slots a sheet of leatheroid is wrapped round the portion which is to be imbedded in the iron, thus protecting the insulating material from mechanical injury whilst the coils are being assembled in position. Other firms are similarly careful in their procedure.

In regard to the actual shape of a former-wound coil, some little ingenuity has to be exercised in shaping that part which does not lie in



Fig. 319.—Portion of Three-Phase Winding of 750-k. w. Armature.

It is also directed that the connections between successive coils of a winding are to be made at the front of the machine only. The slots are 1.85 inch deep by 0.8 inch wide, and the arrangement of the conductors in the slot is shown at A in Fig. 321. There are 10 wires per slot, and as there are 180 slots, this gives 1,800 active conductors for the whole machine, 600 in each phase. The conductors are 0.212 inch in diameter, and are covered with cotton, and braided to a diameter of 0.240, which gives a thickness of insulation of 14 mils. The phases are star connected, and the voltage between lines is 5,300 volts, from which the student can work out the average volts (R. M. S.) per conductor. The full load current is 68 amperes.

The coils, having been placed in the slots, are joined up as shown in



Fig. 320.—Stages in Winding a Large Dick, Kerr Stator.

Fig. 320. Starting from the left hand end of the drawing, we have for the first three slots A-phase coils with straight ends, then three slots with C-phase bent coils coming from the left, and followed by three slots with B-phase bent coils turning to the right. We then come to three slots with the returning sides of the A-phase straight coils with which we started, followed by three slots of C-phase "straight" coils turning to the right, and so on.

It will be appropriate here to refer to a detail given in Fig. 285, namely, one of the high-voltage terminals of the machine. This terminal is carried by a guard attached to the extreme bottom of the frame. It is made of grooved porcelain 2½ inches in external diameter carried by a ½-inch stud fixed to the guard. At the other end the porcelain carries another ½-inch stud, which, in its turn, carries two thimbles, one for the conductor coming from the armature, and the other for the flexible conductor feeding away. To soften the pressure of the metal on the porcelain in clamping up, leather washers are interposed. The drawing gives all the dimensions.

Some of the stages in the assembly of the coils on a stator are shown in Fig. 322, in which the front sector has the bent coils in position with the two ends of each coil loose for the final joining up. The sector imme-

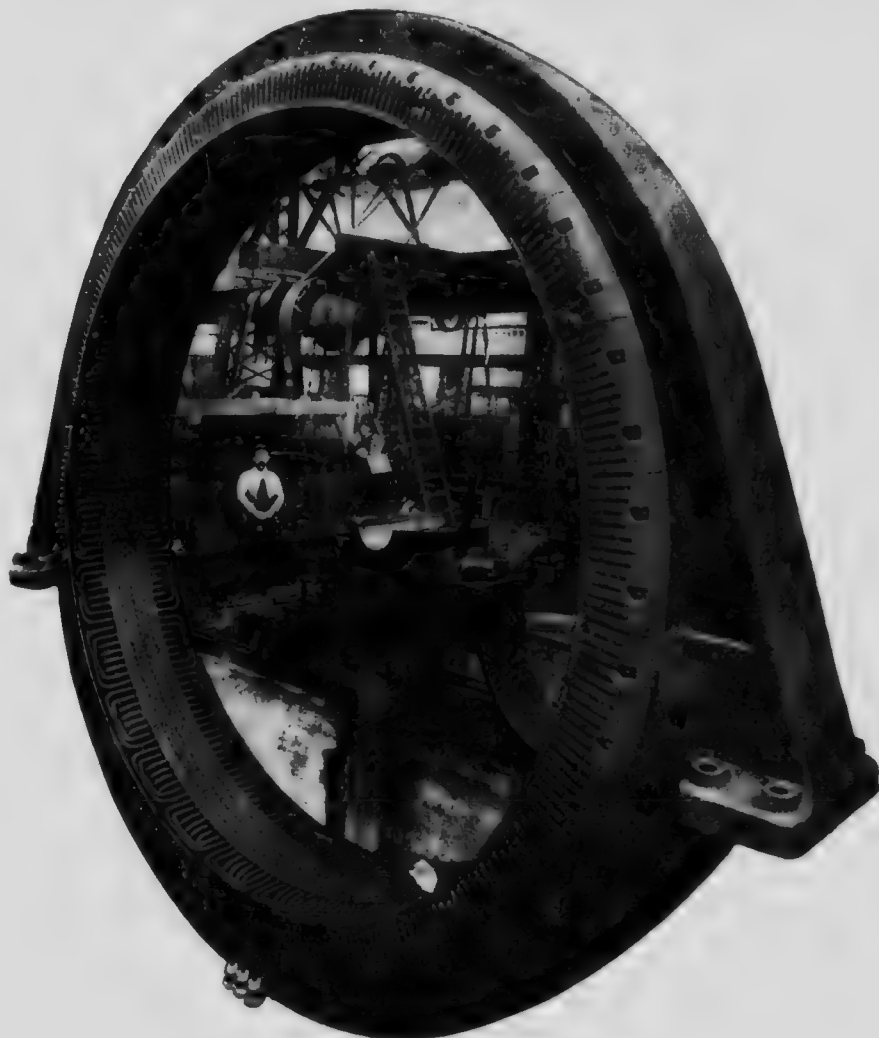


Fig. 323.—Stator of 1,500-Kilowatt Dick, Kerr Alternator.

diately behind has had the flat coils added, but the ends are still lying loose. Lying still farther back unwound sectors are depicted. A completely wound stator, but with double the number of slots per pole is shown

in Fig. 323. Both these figures represent parts of machines built by Messrs. Dick, Kerr and Co., the machine in Fig. 322 being an 800-kilowatt alternator with 64 poles, running at 64 R. P. M.; the winding is for 3,300 volts, three-phase, 50 $\sim$, and the diameter of the rotor is 12 feet 6 inches. The machine in Fig. 323 is much larger, having a rotor 16 feet in diameter which, with double the clearance added, will give the internal diameter of the stator shown, its external diameter being 20 feet 4 inches, from which the radial depth of the stator can be approximately calculated. The rated output of this stator when its 40-pole rotor is running at 75 R. P. M., is 1,500 kilowatts, three-phase at 7,500 volts and 25 $\sim$.

When the voltage required is not high—for instance, when it is only 400 volts, as in the large slow-speed 1,000-kilowatt Brush alternator, already referred to more than once—it is possible to use a simple bar winding very similar to what might be designed for a low-voltage continuous-current multipolar armature. Some details of the winding of the stator of the above-named machine will therefore be of interest. A portion of this stator fully wound is shown in Fig. 324. The core plates and slots have been already illustrated in Figs. 291 and 292, and it will be remembered that the slots are nearly closed, but it will be found presently that the opening left is wide enough to introduce the bars of this winding. Bars of copper



Fig. 324.—Bar-Wound Stator of Brush Alternator.

0.23 inch by 0.40 inch in cross-section, and 40½ inches long are bent accurately to the shape shown in Fig. 325. The complete bars *c n* shown in the figure are actually the terminal bars, which are about 8 inches longer, the ordinary bars being as shown at the side at *A*. Each bar passes twice through a slot of the armature iron, once in the bottom of the slot (indicated by dotted lines) and once at the top (indicated by full lines). At the back it is turned upwards and passes from the lower to the upper level, as shown by the loop at *L*. At the front the ends are bound to the ends of the next succeeding bars, as shown in the sectional detail at *M*. There are five slots between the two positions, the span being an exact pole pitch. Each slot carries the two positions, the span being an exact pole pitch. Each slot carries four bars, two on the bottom and two on the top layer, and as there are two slots per pole per phase and three phases, and also 80 poles, the total number of armature conductors is 1,920.

The winding scheme is shown fully in Fig. 326, which exhibits a sufficiently long section at the bottom of the stator in the neighbourhood of the terminal board, and includes slots 470 to 480, and 1 to 17, or 28 slots in all. The conductors are all numbered, the upper conductors with even and the lower with odd numbers, the connecting parts and the bars being dotted for the lower layer and drawn with full lines for the upper layer. The winding is a three-phase "star"-connected winding, and counting

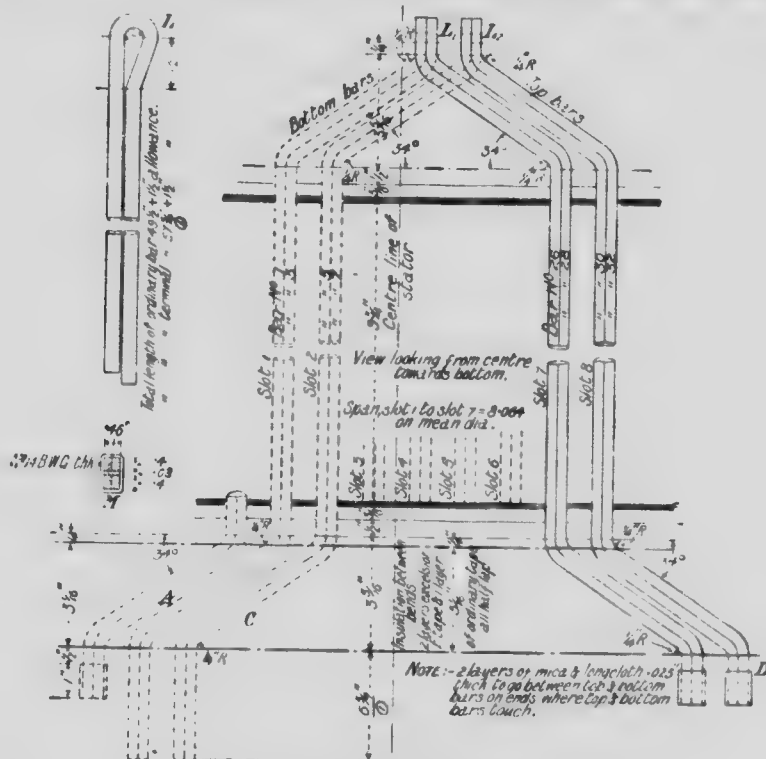


Fig. 325. - Details of Conductors for Bar Winding of Brush Alternator.

each bar in a slot as part of a separate circuit, there are in each phase eight circuits in parallel in two groups of four. The twelve ends of the six quadruple groups are brought out to a terminal board at *t*, *v*, *w*, *x*, *y* and *z*, the phases *A*, *B* or *C* being also marked in the figure.

This terminal board is worth examining; a view of it is given in Fig. 327, and full details on a larger scale are given in the dimensioned drawing reproduced in Fig. 328; whilst a cross-section giving further details, and showing also the protecting cover, is reproduced in Fig. 329. This board carries one "neutral" bar *N* at the top, and three terminal bars *T A*, *T B*,

r c, below. In the upper part of Fig. 328 are shown the ends of the upper and lower groups of leads coming from, u, v, w, etc., in Fig. 326; these upper and lower parts have to be very carefully insulated from one another,

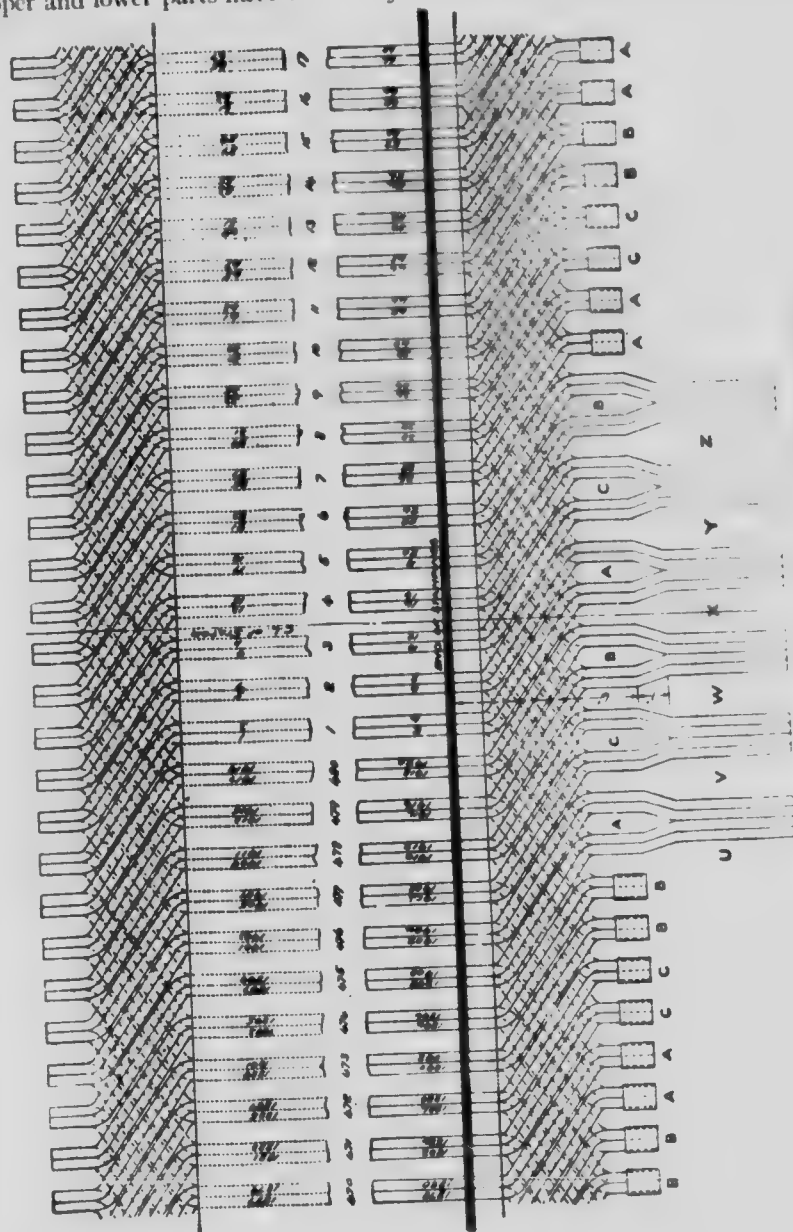


FIG. 326. Winding Diagram

for it will be noticed that in each case they consist of one neutral set, N A, N B or N C, and a corresponding terminal set A, B or C; there is, therefore,



Fig. 327.—Terminal Board of Brush Alternator.

the full pressure of the machine between them, and rigorous instructions are issued that they are to be heavily insulated and kept at a distance apart not less than is marked on the drawing. The terminal thimbles for the cables are shown, and it will be noted that there is a smaller thimble

on the neutral, from which also therefore a cable can be led away.

The appearance of a completed armature of this type, but not for the

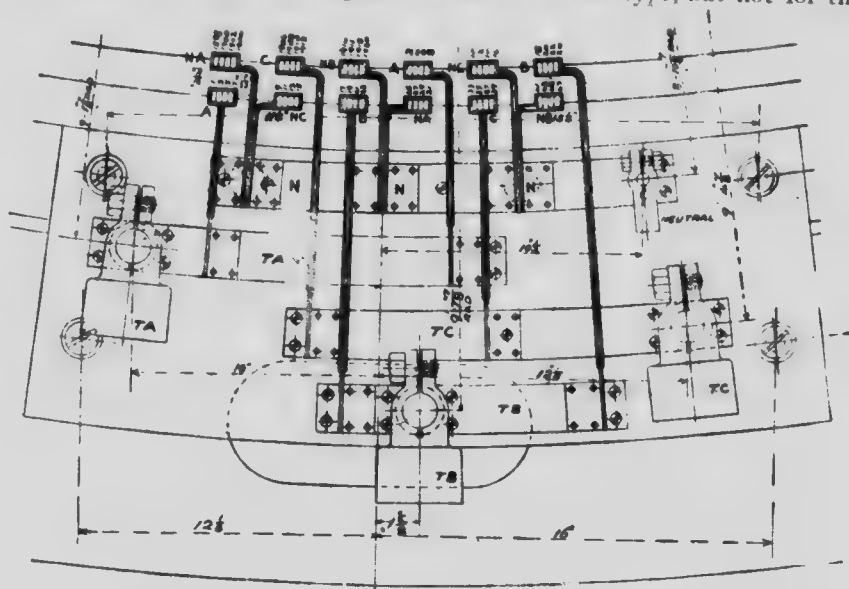


Fig. 328.—Terminal Board of Three-Phase Bar-wound Brush Alternator.

same machine, is shown in Fig. 330, which is the completed stator of a three-phase machine having an output of 350 kilowatts, with a power factor of 0.8 at a speed of 333 R. P. M.; the voltage is 500 volts at a periodicity

A wound armature for a double-inductor alternator, in which the inductor was similar to that depicted in Fig. 277, is shown in Fig. 331. This armature was for a Mordey machine (see Fig. 275), as formerly built by the Brush Electrical

Fig. 379.—Cross-Section of Terminal Board.

for clearness, the slots only of the other phase are indicated by finer lines *s s s*. The connecting wires of the successive coils are at *a a a*, etc., and the width of the two inductor poles and the interpolar distance are drawn to scale. The coils of each phase and the corresponding phases of each armature are in series, so that when the double inductor revolved at a speed of 250 R. P. M., the voltage produced was 2,200 volts in each phase. Each inductor ring carries 12 poles, which at the above speed gave a frequency of 50 ω . The internal diameter of the armature face was 120

inches, and the output 800 kilowatts on a non-inductive load, the maximum excitation being 4.75 kilowatts or 0.58 per cent. of the output. The voltage drop from no load to full load at constant excitation and speed was only 4.1 per cent. The fixed and the rotating parts weighed 16½ and 15½ tons respectively.

Turbo-Alternators.—The general principles to be followed in plan-

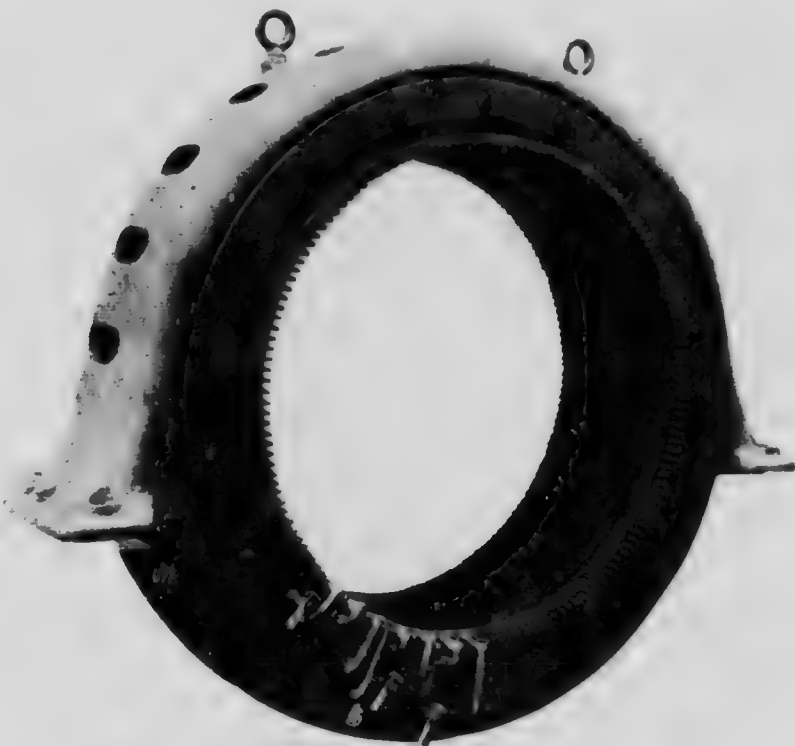


Fig. 330.—Bar-Wound Stator for Brush 350-Kilowatt Alternator (333 R. P. M.).

ning the armature windings of turbo-alternators are the same as for slow-speed machines. As these have just been explained at some length, it is not proposed to recapitulate them here.

The construction of the carcass of a modern alternator armature has been explained and illustrated in the last section. In Fig. 333 is shown, from a photograph, the completed armature or stator of a turbo-alternator built by the British Westinghouse Electric Company. So far as the interior cylindric surface of the armature is concerned, there is nothing but its particular and relative dimensions to distinguish it from the

armature of a slow-speed alternator as depicted in several of the preceding illustrations. A glance, however, at the end connections, to uncover which the end cover of the machine has been removed, shows that these are much more solidly and elaborately clamped, and this, in fact, constitutes the chief difference, beyond that of size, between the slow-

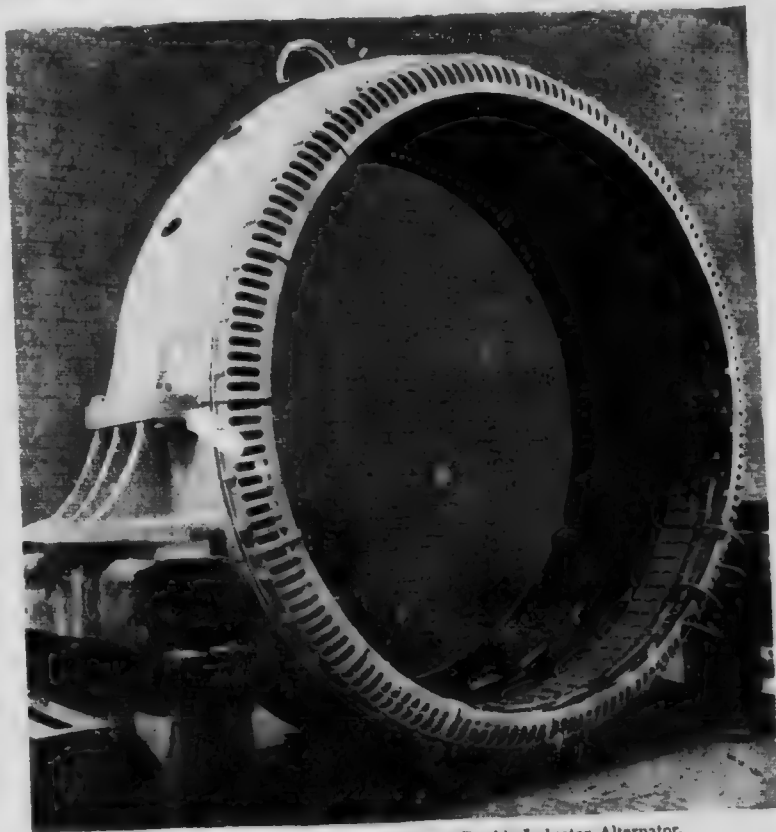


Fig. 331.—Armature of Mordey 500-k. w. Double-Inductor Alternator.

speed piston-driven and the high-speed turbine-driven machines, for we shall see in the sequel that much ingenuity has been expended by different manufacturers in devising these special clamps or bracings.

The cross-section of the copper to be used on the armature windings depends, as in other types of generators, on the full-load current to be carried, and this leads, as elsewhere, to "bar" or "former-wound" coils, the number of turns per phase depending on the voltage to be produced, the speed, the general scheme of connecting, etc.

A bar-wound armature, constructed by the British Thomson-Houston Company, is shown in Fig. 334. It is for a 2,500-kilowatt machine running at 1,500 R. P. M. in a four-pole field. The end shield has been re-

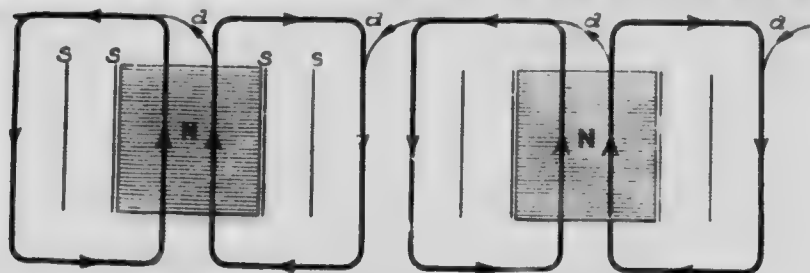


Fig. 332.—Connections of the Coils of a Two-Phase Winding.

removed to show the connections, which, it will be noticed, are very similar to those of the barrel type of bar winding on a continuous current armature. The heavy insulated ring R R, which passes round behind the



Fig. 334.—Westinghouse Coil-Wound Armature.

connecting lugs, is to give the necessary mechanical support to these to enable them to resist any tendency to displacement in the event of an accidental short circuit. The details of the connections, taken, however, from a slow-speed machine similarly wound, can be more clearly seen in Fig. 335, in which a portion of the stator is shown

only partially wound. The open lattice work of the upper and lower connectors sloping in opposite directions, lends itself admirably to cooling by forced air draught in an enclosed turbo-alternator.

The use of former-wound coils for turbo-alternator armatures is illustrated

Fig. 336, which depicts the partially wound stator of a machine built by the British Thomson-Houston Company to give 2,500 kilowatts at a pressure of 11,000 volts when placed in a four-pole field revolving at a speed of 1,500 R. P. M. Here again many of the details are similar to those found at the back end (remote from the commutator) of a continuous current machine with only such changes in form as are necessitated by winding on a concave instead of a convex cylindrical surface. The separate coils are prepared in much the same way and with the same precautions which



Fig. 336.—Partially Wound Stator for B. T. H. 2,500-kilowatt Alternator.

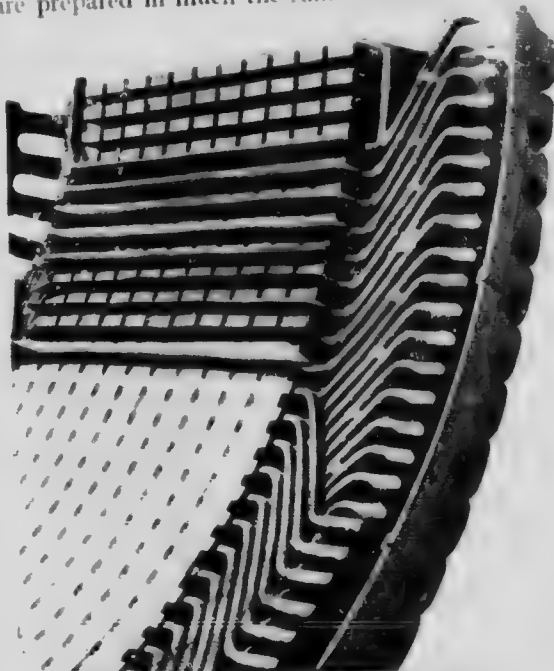


Fig. 335.—End Connections of Bar Windings showing Air Spaces for Cooling.

have been described for both continuous and alternate current generators; and, as usual the connections from one coil to the next in series with it depend upon the scheme of winding. The armature, shown partially wound in Fig. 336, is shown completely wound in Fig. 337, in which, again, the end shield is removed to show the end connections.

(c) **Disc Armatures.**—Although it is theoretically possible to build disc armatures to give polyphase currents, there are certain



Fig. 336.—B. T. H. Partly-Wound Armature for 2,500 Kilowatts at 11,000 Volts, showing Former-Wound Coils.

practical difficulties and disadvantages which have hitherto led to this form of armature being constructed for single-phase currents only.

(a) *Flat Coils.*—These armatures may be either rotating or fixed. Modern examples of alternators with rotating disc armatures have been given in the section on the "magnetic circuit," where the Ferranti "copper-type" alternators (Figs. 226 to 228, pages 233 to 238) have been described. In the same section the fixed disc armatures of the modern Mordey machines have also

been described (Figs. 270 to 272, pages 267 to 270). As the above machines were the most recent ones employing this form of armature further examples are unnecessary, especially as such machines, though still in use, are not now being manufactured.

(b) *Solenoid Coils.*—This form of disc armature was used in the early Gordon machine (Figs. 541 and 542, pages 562 to 564, Vol. I.). The writer is not aware of its being used in any large or important modern machines.

(4) *Pole Armatures.*—Strictly speaking, the armatures of the Mordey inductor alternator (Figs. 276 and 277) and of Kapp's mono-coil alternator, described in the last edition, are pole-wound armatures, but in all these cases the coils are very shallow, and are on the active ends of the armature poles. The term has been more

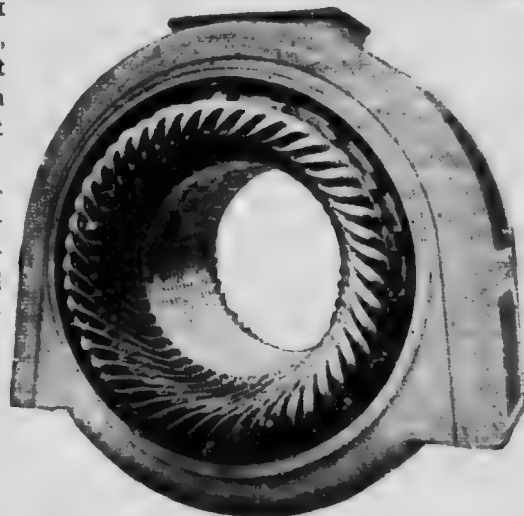


Fig. 337.—Completed B. T. H. Armature for 11,000 Volt Machine.

usually employed to denote those armatures in which the windings extend for a relatively long distance down the core of the laminated polar projections of which the armature iron is made up. Such armatures can, obviously, be only wound for single-phase currents.

The best known of these pole armature machines was undoubtedly the "Hopkinson," the armature of which was fully described in the last edition. In this case the armature rotated and the field magnets were fixed. Pole armature machines with fixed armatures and rotating field magnets were built some years ago by Ganz and Company, of Buda-Pesth, with outputs varying from 10 to 360 kilovolt-amperes at a pressure of 5,000 volts; but this method of construction is now quite discarded in modern alternator work.

V.—TURBO-ALTERNATORS: MECHANICAL DETAILS

Many of the special mechanical problems which arise in the designing of turbo-alternators have necessarily been dealt with in the preceding pages, especially wherever they interlace with magnetic or electrical details. There remain, however, one or two outstanding points which are interesting, and worthy of consideration because of their great practical importance.

Balancing.—Attention has already been directed (see pages 171 to 174) to the necessity for carefully "balancing" the armatures of continuous current dynamos if smooth running is to be secured. The reasons and principles underlying such balancing have been explained, but in view of the exceptionally high speeds of turbo-alternators and of the fact that the centrifugal forces called into play vary as the square of the angular velocity or speed, an additional word of caution will not be out of place here. It is one of the arguments against the salient-pole method of constructing the rotating field magnets that it is difficult to secure a perfectly homogeneous casting for the solid hub and polar projections, and almost impossible to be certain that the desired result has been attained free from internal blowholes and varying densities.

In any case, it must be obvious, whether the rotors are of the cylindrical or the salient-pole type, and in view of the heterogeneity of the materials used and their somewhat miscellaneous distribution in the mass of the rotor, that, however carefully the design may be drafted and the construction carried out, it will be difficult, if not practically impossible, by these alone to secure the desired result. Very careful tests should therefore be made on the completed rotor at speeds well above the normal, and the design should provide for the re-distribution of small masses, so that by a final adjustment a practically perfect balance may result.

Anchoring the End Connectors. Not the least important of the mechanical details in the construction of turbo-alternators are the special supports or bracings, which have to be used to keep the end connections in their places on machines of large output. Such precautions are neces-

sary because of the large mechanical forces which will be brought to bear upon the end connections in the event of an accidental short-circuit occurring during the working of the machine whilst fully excited. As we shall see later, it is possible to short-circuit the armature of a large alternator when unexcited, and then to raise the exciting current to its full value without the current in the short-circuited armature rising to more than two or three times its full-load value. If, however, the short-circuit suddenly occur whilst the machine is fully excited, there may be a momentary rush of current in the armature of more than twenty times the full-load value. This enormous current is, of course, carried by the end connections, which are in the fringe of the rotating field, and

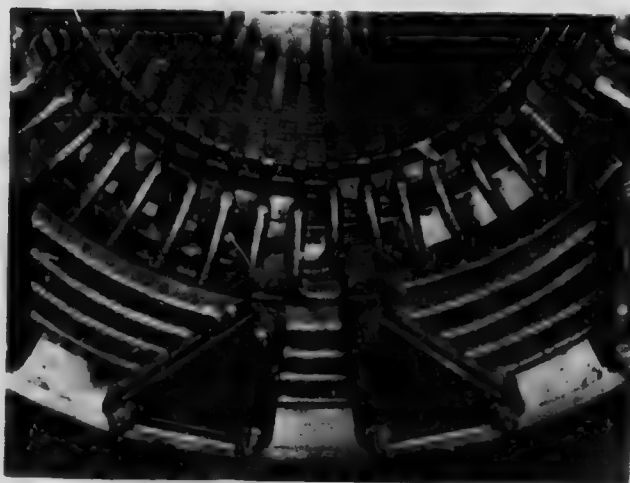


Fig. 338.—Brush: Method of Anchoring the End Connectors.

the mechanical forces called into play may be so great as to drag the conductors out of their positions unless they are securely anchored. It will, therefore, be interesting to examine briefly some of the methods employed to secure the requisite mechanical rigidity.

The Brush Electrical Engineering Company employs substantial clamps, built up of heavy triangular plates securely bolted to the framework of the machine by three studs, as shown in Fig. 338. The connectors for the different phases are at different distances from the iron of the stator, and it is necessary to anchor them very securely in these positions. The figure shows clearly how this is provided for, and in addition to the triangular clamps it should be noted that the straight parts of the coils as they come out from the slots are held apart by wooden wedges. The machine of which this is a part is a 2,000-kilowatt machine. A complete stator of a similar machine, as shown in Fig. 339, will assist the reader to understand the details of the clamping.

A somewhat similar method is employed by Messrs. C. A. Parsons and Co. to anchor the end connections of their large turbo-alternators. The method is shown in Fig. 340, which is a line diagram taken from a paper

read by Mr. T. P. E. Butt before the South African Institute of Engineers. This paper sets forth the details as worked out for one of the 6,000 - kilowatt turbo-alternators supplied to the Randfontein Central for their power station on the Rand. The rotor of the machine is about 7 feet in diameter and runs at 1,000 R. P. M. to supply three-phase current at 50 periods per second and 6,600 volts between phases.

The clamps, of which there are nine, are in the shape of a quadrilateral, with unequal sides, about 3 feet in extreme length, and in the radial direction on the machine about 20 inches wide. They clamp down the end connectors in groups and are held firmly in place by four bolts in

each clamp as shown; they are also braced together by rods, and some subsidiary clamps are also shown.

The method of bracing used by the British Westinghouse Electrical Company has already been shown in Fig. 333. Each set of clamps used is bolted to the body of the machine by two bolts. It should be noticed that the connectors are so placed relatively to

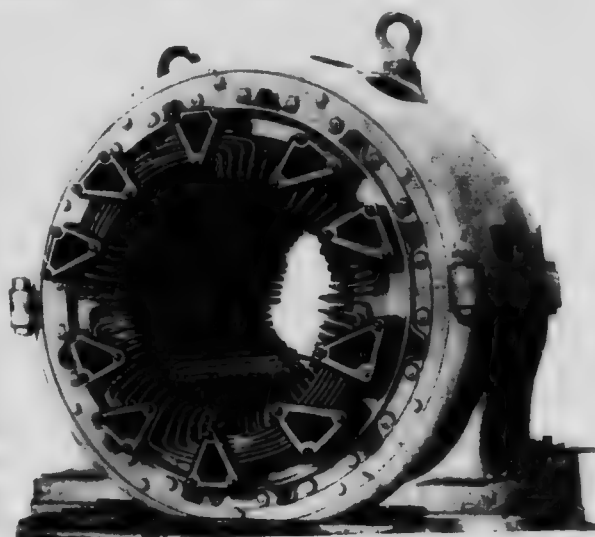


Fig. 339.—Coil-Wound Armature of Brush Turbo-Alternator, showing Clamped End Connectors.

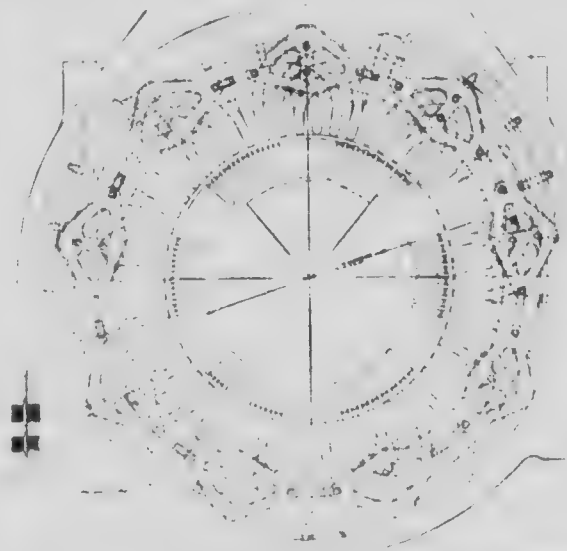


Fig. 341.—Diagram of Clamped End Connectors. Parson's 6,000 Kilowatt Turbo-Alternator.

one another as to provide ample interspace for the circulation of the air used for cooling purposes.

As another example of a somewhat different method of bracing, Fig. 341 shows the details in this respect of an 850-kilowatt bipolar generator built by Messrs. Dick, Kerr and Co. In this case substantial brackets projecting from the body of the machine are used to hold the connectors

inplace. These connectors are spaced well apart in two layers, each having its pattern of bracket designed for the particular distance. Again, as in the last example, ample space is left for the ventilating air currents. Another, and even clearer example of this method of bracing will be found in Fig. 342, which shows the large Dick, Kerr 8,000-



Fig. 341.—End Connectors of Dick, Kerr Alternator.

k. v. a. alternator with the end plate removed, and with its rotor (see Fig. 304) in position.

Other methods of anchoring the end connectors of rotors have been shown in some of the illustrations in the preceding pages, especially that which aims at securing them firmly by means of an end flange or cap. An additional example of this method is given in Fig. 343, which shows the rotor for a 5,000-kilowatt Curtis turbo-generator as built by the British Thomson-Houston Company. This should be compared with Fig. 302, which shows a similar rotor partly wound, when it will be seen that the broad bands which form the end connectors have been covered by a massive flange bolted

firmly with a broad annulus or ring to the magnet iron. Incidentally, it may be noted that the figure shows the slip rings for leading in the current.

Ventilation.—The sizes of turbo-alternators have increased very rapidly of late years, and the largest machines have now an output far in excess of the output of the largest slow-speed machines as yet built. This development is in part due to the readiness with which the size of steam turbines can be increased without becoming unwieldy, as is the case with reciprocating engines, and also in part due to the compactness of the electric generator, which in this respect matches the turbine prime mover. But, as has already been pointed out, this increase of size introduces new mechanical problems, which must be solved, in addition to the electrical problems dealt with in the immediately preceding pages.

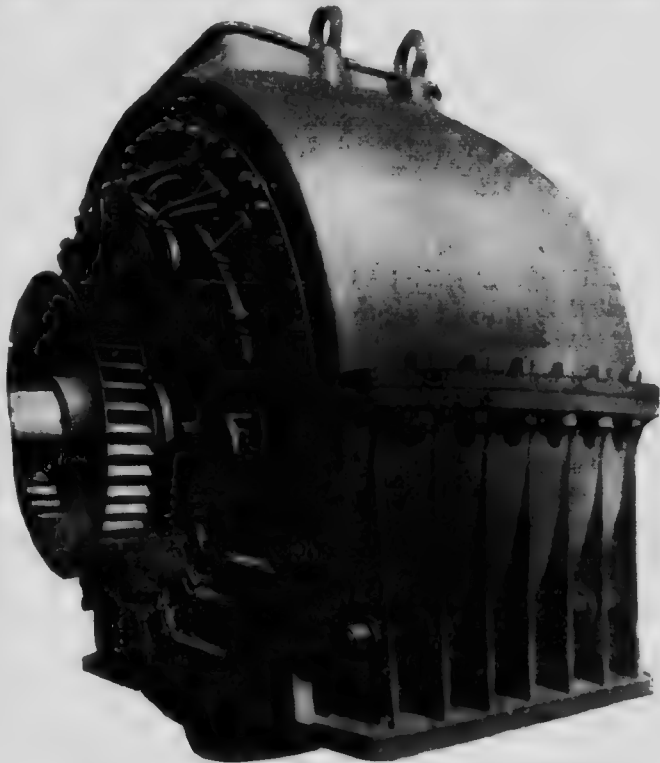


Fig. 142.—Bracing of End Connectors of Dick, Kerr 8,000 Kilowatt Alternator.

One of the most important of these is how to deal with the waste heat produced by the *inefficiency* of the machine itself, for, as has been remarked over and over again in these pages, all the losses arising from the imperfect conversion of the energy transmitted to the shaft by the prime mover into the electric energy which is led away into the external circuits by the mains appear eventually as low-grade waste heat. Thus, in a 5,000-kilowatt machine, on the assumption that the efficiency at full load is as high as 97 per cent., the power lost by conversion into heat is 150 kilowatts, and it is being produced within the machine at the corresponding rate in heat units per second. Now a slow-speed multipolar machine of this size, as an

inspection of the illustrations already given will prove, has its working parts, in which the waste heat is being produced, fairly well exposed to the cooling influences of the surrounding atmosphere and of the cool air which

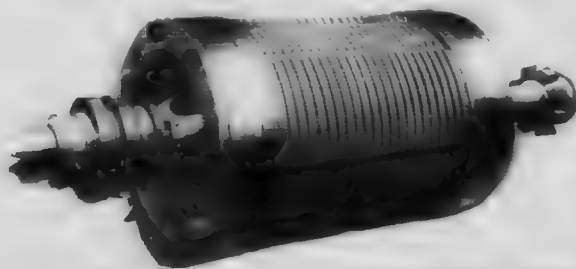


Fig. 343.—Curtis-Knowlton Alternator, showing the method of drawing cool air.

the rotation of the field magnets directly reaches through the ventilating ducts of the armature. But in the turbo-alternator not only is the machine smaller in size, leading therefore to a greater concentration of the heat, but it is also, and necessarily, much more completely enclosed.

At the end plates of the casing, usually introduced to direct the ventilating air and to protect the end-connectors, are omitted. As machines are now being built of five times the size just mentioned, the satisfactory solution of the problem of ventilation has become extremely important.

The general solution for the turbo-alternator is to draw the air from the bottom of the machine, where the heat is being produced, and to discharge the heated air into the atmosphere passing through the casing, so that the engine room temperature is also kept reasonably low.

The details of the method differ with different designers, and some of them have already appeared in our illustrations.

The method adopted by Brown,

Boveri and Co., is simply shown in Fig. 344. The two end plates of the rotor (see Fig. 298) carry fan-blades, or impellers, as they are sometimes called, of sheet metal so shaped that, when the rotor rotates, they drag air up from a tunnel below and drive it through the machine. This air, if it be considered necessary, can be cleaned and cooled at the

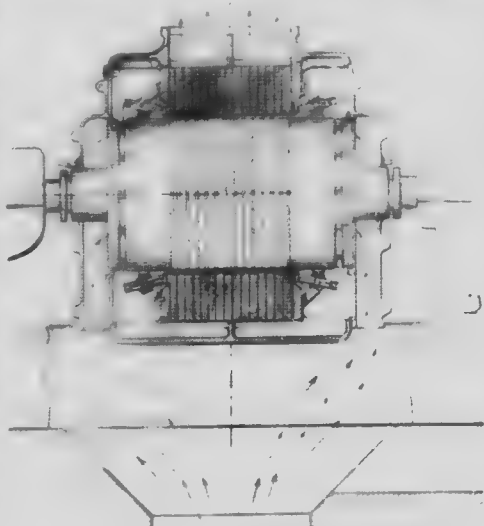


Fig. 344.—Brown, Boveri & Co.'s Method of Ventilating Turbo-Alternators.

distant inlet before entering the tunnel. Its course is shown by the arrows as, dividing right and left, it streams up towards the fan blades at each end of the rotor, after passing which it divides into two streams: (i.) one entering the longitudinal ducts behind the core plates of the rotor and being forced between these core plates and discharged against the heated conductors of the armature; (ii.) the other entering ventilating ducts behind the armature stampings. These streams, in their numerous

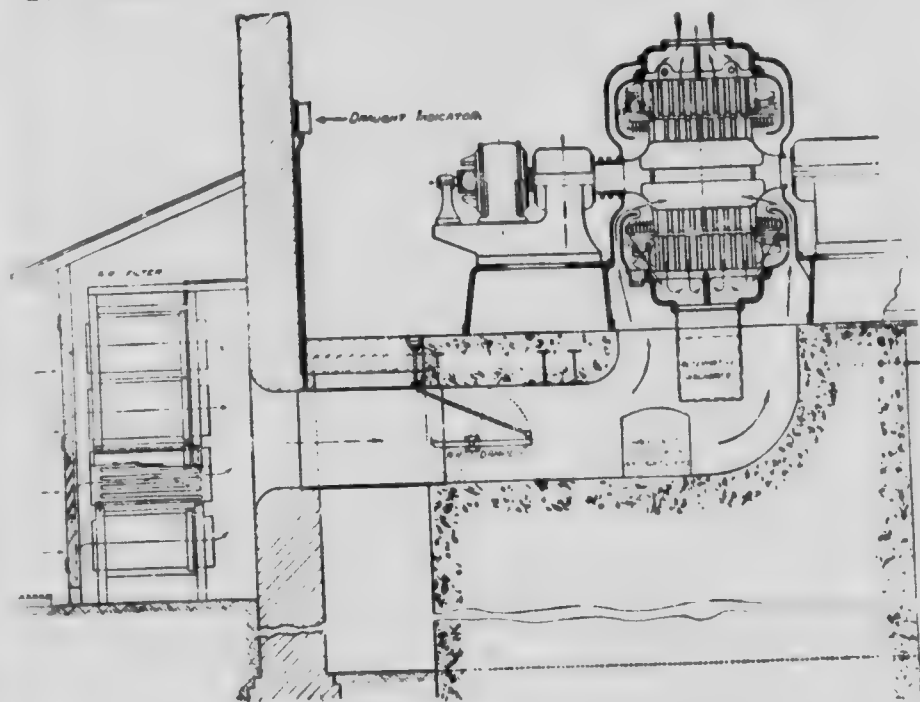


Fig. 145.—A Ventilating System for Turbo-Alternators.

sub-divisions, all re-unite at the top of the machine casing where they enter a chimney and are carried away harmlessly. The Brown, Boveri dynamo of Plate IV. is worthy of study in this connection.

In the Curtis turbo-alternator of the British Thomson Houston Company the chimney space immediately behind the armature core plates is separated from the rest of the space inside the housing. The air coming in from the outside finds its way first to the central shaft (see Fig. 143) when it is caught and projected through the slots of the rotor against the face of, and through the slots of, the stator into the above annular space. By suitably placed screens part of it is diverted and passes over the end connections. Having reached the annular space, it can then either be

discharged into the room or led away through a suitable chimney or a discharge pipe beneath the floor.

The whole system is shown diagrammatically in Fig. 345. The air, after passing through a suitable air filter in a room outside the engine-room, enters a duct leading to the alternator, through which it passes as described above. The quantity of air can be regulated by a damper, a

"draught indicator" giving some idea of the conditions at any moment.

A still more elaborate system of air ducts is provided in the turbo-alternator of the Electric Construction Com-

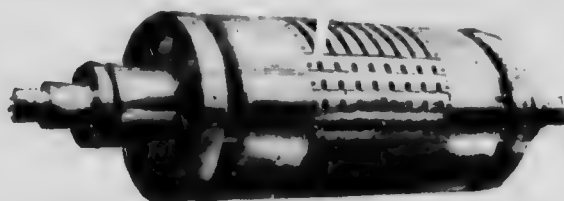


Fig. 346.—Completed Brown, Roveri Rotor, showing Ventilating Fans on Shaft.

pany, shown in Plate VII. There are no fewer than four air inlets in the base of the machine, two at each end. This ensures that reasonably cool air shall reach each important part of the machine direct before the air has been warmed by passing through other parts. The courses of the various streams are clearly shown by arrows, especially in Fig. 294, and detailed description is therefore unnecessary; but the reader is strongly

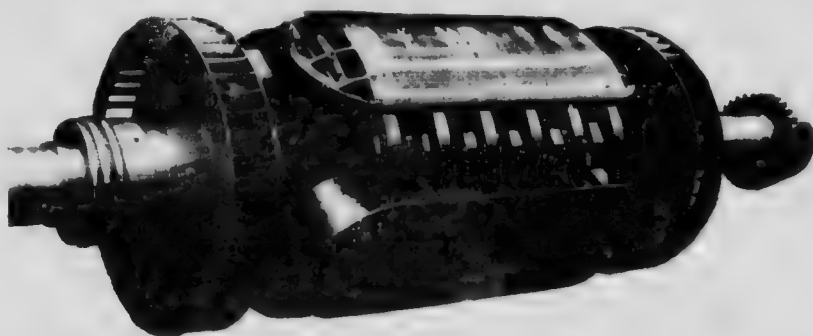


Fig. 347.—Rotor of 8,000-K. V. A. Dick, Kerr Turbo-Alternator, showing Ventilating Fans.

recommended to trace the courses out for himself and to note the careful way in which the housing has been designed to attain the objects in view.

It has been explained that, in many cases, to obtain a good draught through the heated parts of the machine sheet metal impellers of suitable shape are fixed in proper positions on the rotor. Many firms go farther and build up at the ends of the rotor what are virtually, if not actually, fans designed so as to propel the air through the machine. An illustration of this is given in Fig. 346, which shows the completed rotor

of a small Brown, Boveri alternator constructed as shown in Fig. 298. In passing, it may be pointed out that in this case the slip rings for supplying current to the field magnets are placed one at each end of the body of the magnet.

Messrs. Dick, Kerr and Co. have the fan even more detached, as shown in Fig. 347, an illustration of a four-pole rotor with salient poles; the details of the construction of which have been already described. The

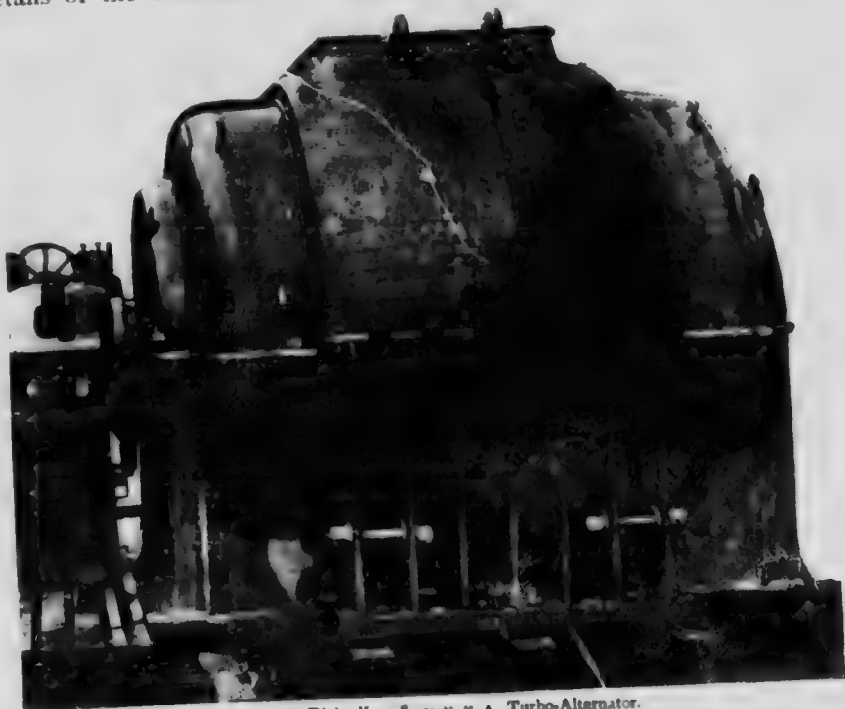


FIG. 347.—Dick, Kerr 8,000-K. V. A. Turbo-Alternator.

machine, with the rotor in position, but with the end covers removed, is shown elsewhere (Fig. 342), whilst the complete machine, mounted on the test bed, ready for testing, is illustrated in Fig. 348. It is a machine designed to give the very large output of 8,000 K. V. A. at 750 R. P. M., an output greatly in excess of the largest steam-driven slow-speed alternator yet built. The end shields, which cover the fans seen in Fig. 342, can be clearly made out in Fig. 348; they are so shaped that they can lead the cooled air supplied from suitable ducts below the machine direct to the fans, by which it will be propelled into the working parts of the machine, and by suitable deflectors will be ultimately directed towards the opening at the top, from which it can be discharged into a suitable chimney.

For the large output named the quantity of heat to be carried off at full load, even at high efficiencies, will be very considerable.

Terminals.—In large turbo-alternators the terminals of the armature windings are usually placed at the bottom of the machine so that the current can be led away by cables laid in trenches to the controlling switch-

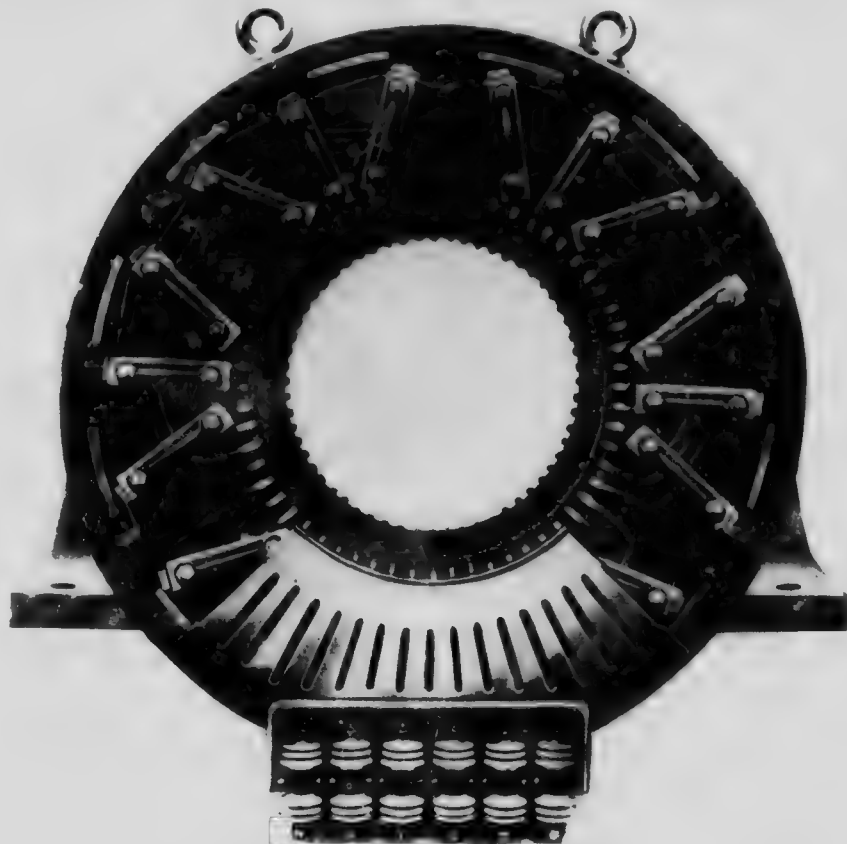


Fig. 349.—Terminals of Peebles Three-Phase Alternator.

board. The insulation of these terminals is, of course, carefully designed, especially in high-voltage machines. An example is given in Fig. 349, which shows the armature of the Peebles standard open-type turbo-alternator with the end shield partly removed. There are, in this case, six terminals, both ends of each of the three-phase windings being brought out so that they may be connected in star or mesh.

Another example is given in Fig. 350, which depicts the standard type of three-phase turbo-alternator built by the Lancashire Dynamo and Motor

Company, Limited. Here only three leads are brought out, the windings of the armature being permanently star-connected with the neutral point not made directly accessible. The terminals of the 6,000-kilowatt Parsons turbo-alternator on the Rand can be seen at the right hand of Fig. 190, and some of the illustrations of other machines also show high voltage terminals.

VI.—ELEMENTARY THEORY OF ALTERNATORS

The general principles of magneto-electric induction and of the magnetic circuit upon which the quantitative laws which govern the design and

working of alternators are based are the same as for the corresponding cases of continuous current dynamos, which have already been treated at some length. It is not intended to repeat here what has been said elsewhere in the book, but rather to supplement and

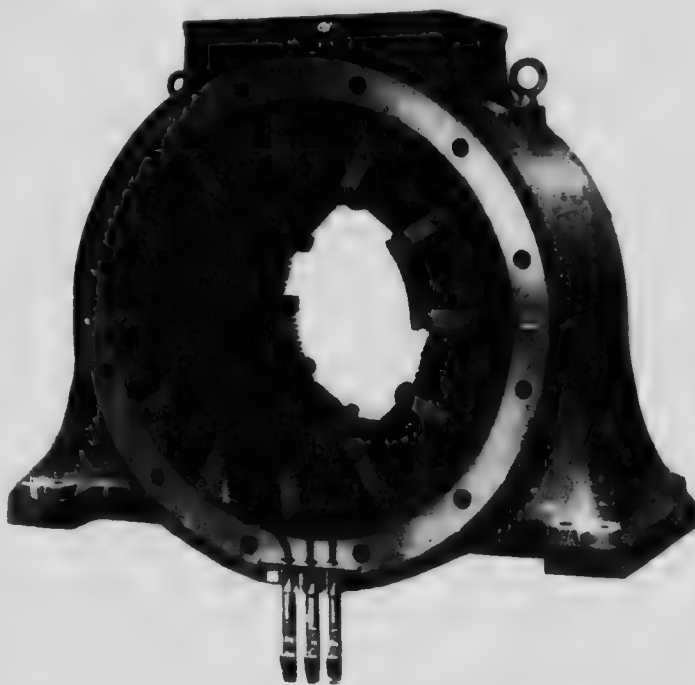
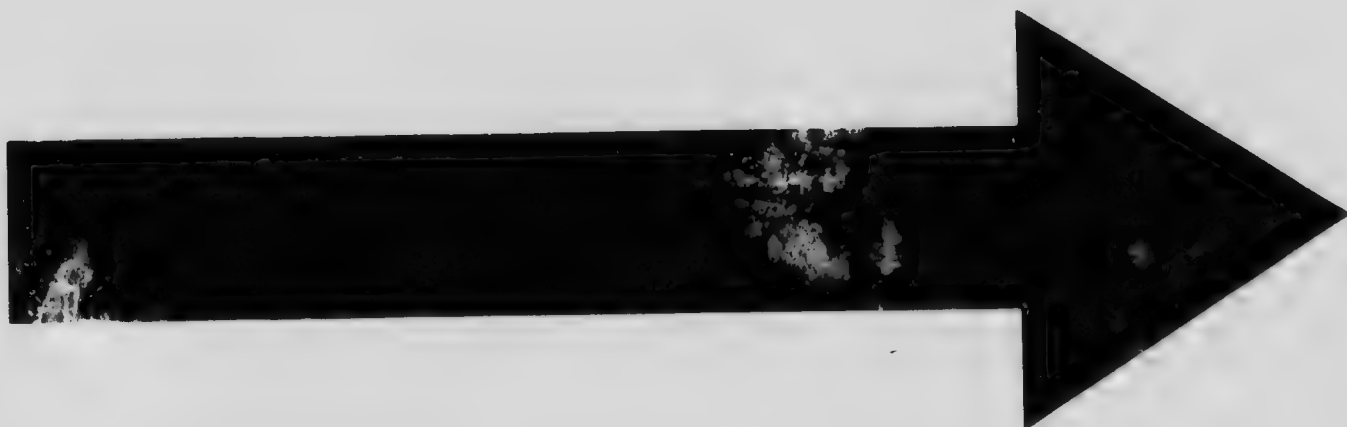


Fig. 190.—Armature of Lancashire D. & M. Co. alternator.

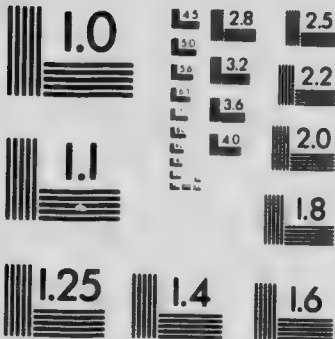
extend it, and to exhibit the differences which arise in applying the main principles to the special cases of the various forms of alternators. Some of these differences have already been dwelt upon somewhat fully as they have arisen in the preceding pages in connection with the details of design and construction of the various types of machines, and in taking up a few outstanding points of special interest recapitulation of more than is absolutely necessary will be avoided as far as possible.

Calculation of E. M. F.—Two general cases arise (a) the case in which the windings are uniformly distributed round the periphery of the



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armature, and (b) the case in which the active conductors of any particular circuit are in small groups with intervals between, either (*b*₁) laid on the active surface of the armature (slots and tunnels being included in this division), or (*b*₂) coiled on cores or polar projections at regular intervals round the periphery. In what follows we shall use the same symbols as when dealing with continuous current machines (*see* pages 483 and 513, Vol. I.), with the addition in multipolar machines of the symbol *p* to denote the number of *pairs* of poles and using the symbol *ϕ* to denote the flux from any *one* pole.

(a) *Distributed Windings*.—The cases in which the windings are evenly distributed throughout the active belt of the armature are very similar to the corresponding continuous current cases. In what follows the distance from the middle of an *N* pole to the middle of the adjacent *S* pole, or any equivalent distance measured in the direction of rotation, will be referred to as the *pole pitch*. We have therefore,

$$\text{Time of a complete revolution} = \frac{1}{n}.$$

$$\text{Time of passing over one pole pitch} = \frac{1}{2pn}.$$

$$\text{Flux per pole} = \phi \quad (\text{maxwells}),$$

$$E_{\text{avg.}} \text{ per conductor} = \phi \div \frac{1}{2pn} = 2pn\phi.$$

Two cases now arise:—

- (i.) The conductors may be joined in parallel groups to two slip rings electrically equivalent to the manner in which at any instant the conductors of a multipolar dynamo are joined to the collecting rings through the brushes. In this case we have

$$\text{Number of conductors in series} = \frac{Z}{2p},$$

and therefore

$$*E_o = 2pn\phi \times \frac{Z}{2p} = nZN \quad (1)$$

- (ii.) The conductors may be joined in series in groups equal in circumferential length to the pole pitch, and these groups so connected that at the instant of maximum induction in each group all the *E. M. F.*'s in the circuit are in the same direction. In this case we have

$$\text{Number of conductors in series} = Z,$$

and therefore,

$$E_o = 2pn\phi \times Z = 2pnZN \quad (2)$$

The windings in this case do not form a closed circuit, but are cut for connection to the slip rings at the junction between two groups.

- (b) *Grouped Windings*.—The cases coming under this heading are

* For the meaning of *E_o* *see* page 542, Vol. I.

numerous, and are not amenable to the same simple methods of calculation as those just considered. In a general way it may be said that the value of E_0 , the maximum E. M. F., depends upon the quantity $n Z N$, and where as many groups as there are pairs of poles are joined in series it further depends upon the product $p n Z N$. But it is obvious that the value of the maximum E. M. F. at the instant when, on the whole, the conductors of a single group or coil are most rapidly cutting the lines of force of the field depends upon the relation between the grouping of the conductors (usually known as the breadth of the coil) and the distribution of the magnetic flux. The above expression must therefore be multiplied by some coefficient k_0 which depends upon the relation between the breadth or arrangement of the conductors of each group or coil, the width of the pole faces, and the pole pitch. We have, therefore, finally,

$$E_0 = k_0 p n Z N \quad (3)$$

which may be taken as the general formula for alternators, in which the $2 p$ groups are all in series, and includes the case (a) (ii.) above, when the value of $k_0 = 2$.

Measured E. M. F.—The above calculations give the value of E_0 , the maximum ordinate of the E. M. F. curve. But it has been shown (see page 766, Vol. I.) that our measuring instruments do not give readings of this quantity, but usually of another quantity—namely, the *root mean square* of the volts. Further, the relation between the values of E and the R. M. S. (*root mean square*) depends upon the shape of the E. M. F. curve. If this curve be a sine curve it is shown that

$$E_{r.m.s.} = \frac{E_0}{\sqrt{2}} = 0.707 E_0 \quad (4)$$

If the curve be not a sine curve, but have some other shape—for example, one of the curves of Fig. 514, Vol. I.—the relation between $E_{r.m.s.}$ and E_0 may be very different, and must be ascertained for the particular curve under consideration. For the value of $E_{r.m.s.}$ or E_v (*virtual volts*), as we may call it, k_0 in the equation (3) must be replaced by another coefficient k_v , and then we have for the volts as read on an ordinary voltmeter properly calibrated

$$E_v = k_v \times p n Z N \quad (5)$$

Professor Kapp has calculated the value of k_v for various widths of poles and breadths of coils, the field under each pole being supposed uniform. His results are embodied in the following table:—

Pole Width.	Total Breadth of Copper in Coil.	k_v
1. Equal to pitch	Equal to pitch (covering whole surface)	1.100.
2. Equal to pitch	Half of pitch (covering half of surface)	1.035.
3. Half of pitch	Equal to pitch (covering whole surface)	1.035.
4. Half of pitch	Half of pitch (covering half of surface)	2.300.
5. Third of pitch	Third of pitch (covering third of surface)	2.830.

For a disposition of windings and field that would give a simple *sine-law* wave of E. M. F. we should have $k_v = 1.414$ (i.e. 2×0.707).

For any other case the values of k_o and k_v can be found graphically, although the process is laborious, by first plotting the field intensity for the whole of the pole pitch and reducing therefrom the E. M. F. in each of the conductors in each slot in various positions along the pole pitch; from these results the wave form can be plotted to scale, and then the determination of k_o and k_v follows easily. For each phase of a polyphase machine Mr. Eborall* gave the value of k_v as lying between 2.1 and 2.3, the average and most common value being 2.2, and z being the number of conductors in each phase.

Polyphase Pressure.—The calculations for the generated E. M. F. in machines wound for polyphase currents follow the lines set forth above for single-phase currents, but when it is required to calculate the pressure between the terminals attention must be paid to the internal connections.

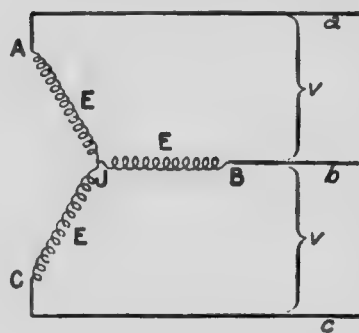


Fig. 351.—Three-Phase Line Pressure.

In the manner shown the E_o and E_v for each phase can be calculated separately. With two-phase machines, where the phases are entirely distinct, the usual case (see Fig. 529, Vol. I.), the voltage in each circuit will be as calculated, whilst the voltage (V) across the lines of the different phases will be

$$V_o = E_o \div \sqrt{2} = 0.707 E_o,$$

$$V_v = E_v \div \sqrt{2} = 0.707 E_v.$$

For three-phase machines, in machines "mesh" connected, the pressure between lines is the same as the calculated pressure generated in each phase—i.e. either E_o or E_v . For the "star" connection, however, the calculation will first be made for a single-phase A J, B J, or C J (Fig. 351); the pressures so calculated will differ in phase by one-third of a period (120°), and the pressure between any two lines— a and b , for instance—will be the vector sum of the pressures in the adjacent phases, and therefore

$$V = E_o \times 2 \sin 60^\circ = \sqrt{3} E_o = 1.73 E_o,$$

$$V_v = E_v \times 2 \sin 60^\circ = \sqrt{3} E_v = 1.73 E_v.$$

Other cases can be similarly treated.

Armature Reactions.—The armature reactions in an alternator are governed by the same principles as those applying to continuous current machines (see pages 502 to 505, Vol. I., and 100 to 129, Vol. II.), but are complicated by two additional conditions, namely:

- (i.) The magnetic strength of the armature as an electro-magnet varies in magnitude from a maximum to zero.

* *The Electrician*, Vol. XLVII., page 144 (1901).

- (ii.) The effective magnetic poles of the armature electro-magnet in a single-phase armature alter their position in space during every half period, and this position is affected by the phase of the armature current and by hysteresis.

It will therefore be simplest to consider first the character of the armature reaction, neglecting both lag and hysteresis.

Lag and Hysteresis Neglected.—For simplicity, take a bipolar machine (Figs. 352 to 356), with evenly distributed closed-coil windings and two diametrically opposite conductors A and B connected to the slip rings. The adaptation of the reasoning to the case of multipolars will offer no difficulty. We shall also use the same method of analysis as was employed for continuous current machines (*loc. cit.*).

When the line of the slip-ring connections A B is horizontal (Fig. 352) the E.M.F. is zero, and so is the current, since,

by hypothesis, there is no lag, and in the absence of hysteresis the iron of the armature has no magnetism due to currents in the conductors, although it is, of course, magnetised by the field of the dynamo.

As the armature swings round towards the position of Fig. 354, when the line of the slip rings is vertical, the current increases to a maximum, and the current-carrying conductors may be divided into two belts: (i.) a *magnetising belt* between the vertical lines *a d* and *b c* (Fig. 353), and (ii.) a *cross-magnetising belt* outside these lines.

Of these the effect (i.) of the magnetising belt is zero at the two extreme positions (Figs. 352 and 354), because in the first position there is no current and in the second position there is no belt. It rises to a maximum somewhere between these positions, where the ampere-turns between the lines *a d* and *b c* are a maximum, for the amperes are continuously increasing whilst the turns are continuously diminishing between the limits. On the other hand, the effect (ii.) of the cross-magnetising belt continually increases on account of the increase both of the amperes and of the turns until it reaches a maximum in Fig. 354.

Between the positions in Figs. 354 and 356 a similar series of changes takes place, with these differences: (i.) That the magnetising belt of Fig. 353 becomes a *demagnetising belt* between the vertical lines *a d* and *b c* in Fig. 355, in which the demagnetising ampere-turns rise from zero (Fig. 354) to a

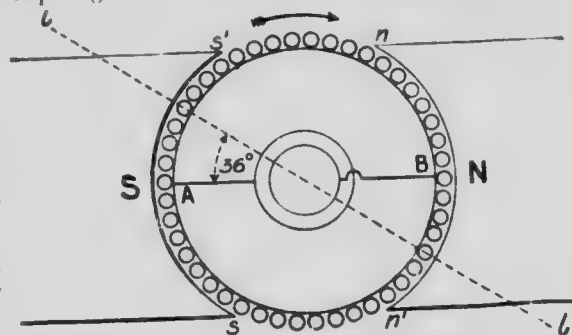


Fig. 352.—Bipolar Alternator, "No-Current" Position (U' is Power Factor)

maximum, and fall again to zero (Fig. 356); and (ii.) the cross-magnetising ampere-turns sink from a maximum to zero.

At Fig. 35f the whole series of changes commences again, but with the B conductor taking the place of the A conductor, and vice versa.

To sum up, the effect of the armature current in the special case considered may be regarded as a combination of (i.) an alternate magnetising and demagnetising flu.. of twice the periodicity of the machine, and (ii.)

a pulsating cross-magnetising flux which is always in the same direction, but rises twice to a maximum and sinks twice to zero in a single period. Both these varying fluxes will give rise to eddy currents in non-laminated pole faces.

Effects of Lag.

—It is now easy to trace the effects of lag. With a lagging current the position in Fig. 352 will not mark the close of the demagnetising effect, for there

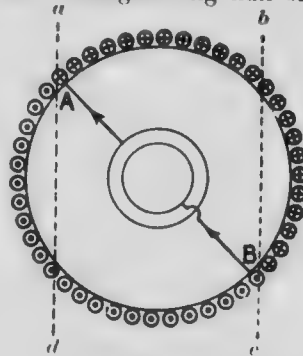


Fig. 353.—Current Increasing.

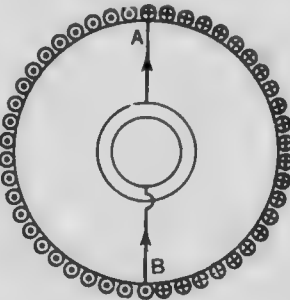


Fig. 354.—Current a Maximum.

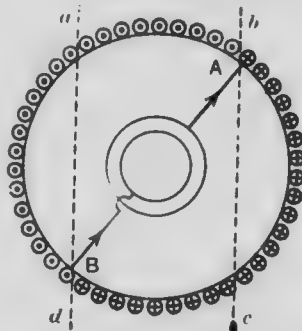


Fig. 355.—Current Decreasing.

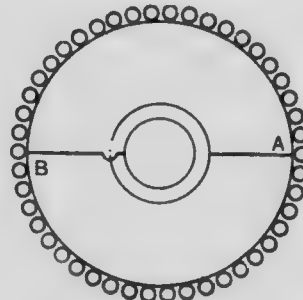


Fig. 356.—Current Zero.

Bipolar Alternator Armature with Non-Inductive Load; Field Horizontal.

will still be current in the conductors, which are all now included in the demagnetising belt. The demagnetising effect will continue until the current reverses, which may be when the line A B is in a position well removed from the horizontal. The actual angular distance will be determined by the power factor, and will be such that the cosine of the angle with the horizontal will be equal to the power factor. For instance, if the power factor be 0.8, we find that $\cos 36^\circ 51' = 0.8$, and in this case the reversal from demagnetising to magnetising effect will not take place until A B has moved forward through $36^\circ 51'$ to a position marked approximately by the dotted line $l'l'$ (Fig. 352). As the next

reversal is bound to be in the position of Fig. 354, because of the disappearance there of the magnetising belt, the effect is to prolong the demagnetising period and shorten the magnetising period, and it is also obvious that the maximum demagnetising ampere-turns will be greater than the maximum magnetising ampere-turns.

In this case also the cross-magnetising ampere-turns will not always be in the same direction as in the preceding case, but between the positions AB and $11'$ (Fig. 352) they will be reversed in direction, and will tend to strengthen the flux at the leading poles ns instead of the flux at the trailing poles $n's'$. The greater fluctuating increment, however, will still be at the trailing poles.

The effect upon the field flux of the first part (i.) of the reaction may be shown graphically by the curves of Figs. 357 and 358, in which the horizontal line FF' denotes the total flux set up by a steady current in the field magnets. In both figures the position marked 0° corresponds to the position shown in Fig. 352, 90° corresponds

to Fig. 354, and 180° to Fig. 356. In Fig. 357 the current and E. M. F. are supposed to be in step, the power factor being unity. The effect of the magnetising and demagnetising belts is shown by the curved line; from 0° to 90° it increases the field flux, from 90° to 180° it diminishes it; but the $+$ and $-$ loops are equal, and the mean value of Φ remains unchanged. The effect of the pulsation, however, in generating current in solid pole faces must not be lost sight of. In Fig. 358 we deal with the case of a power factor of 0.81 and a consequent lag of 36° . The curved line which now denotes the effect of the above belts is lowered with respect

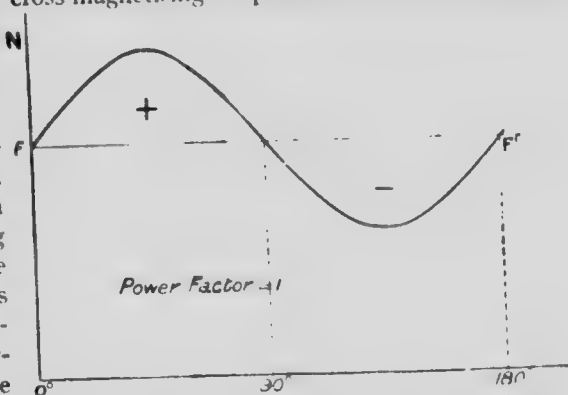


Fig. 357.—Armature Reaction; Current and E. M. F. in Step.

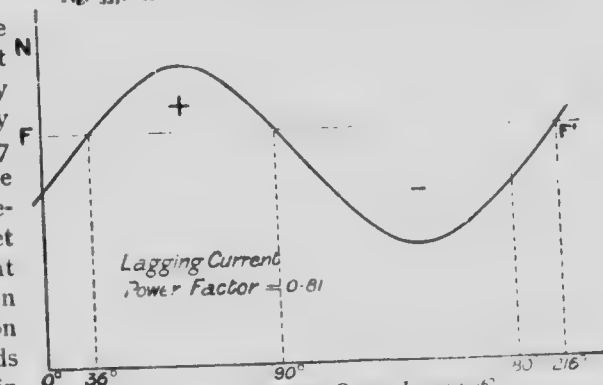
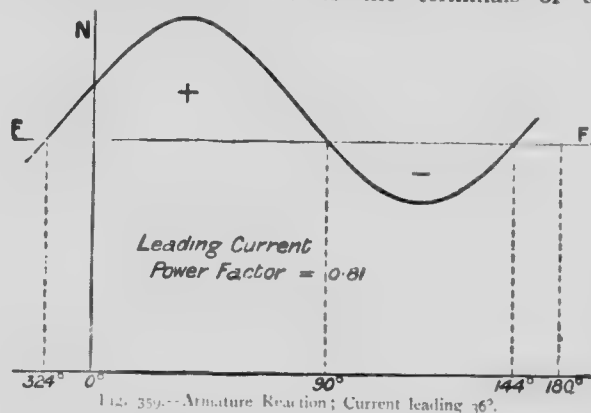


Fig. 358.—Armature Reaction; Current Lagging 36° .

to the line EF' and also moved to the right, so that the two crossing points occur at 36° and 90° respectively. The effect now is to increase the flux between 36° and 90° , and to diminish it between 90° and 216° . Moreover, the $-$ loop is now much larger than the $+$ loop, so that on balance there is a demagnetising effect and the *mean* value of N is lowered.

In these figures the curves have been drawn as sine curves; with the usual current waves they will be more irregular, but the general result will be as indicated.

The percentage magnitude of the demagnetising effect on the field in any given case will depend upon the relative values of the field magnets and the armature as electro-magnets, the latter depending, of course, on the inductance of the armature. Hence it is possible to place a dead short circuit across the terminals of some alternators with-



out damage to the machine, although the full excitation current is flowing in the field coils. The explanation is that the heavy currents produced have so great a lag that their demagnetising effect on the fields is sufficient to reduce the total flux to such a value that the E, M, F , obtained is

only sufficient to maintain a harmless current in the short-circuited armature.

Effects of Lead.—By the same process of reasoning which we have employed above, it may be shown that the effects of a leading current in the armature coils are

- (i.) An alternate magnetising and demagnetising action in the field in which the magnetising action is the greater, so that the *mean* value of the flux is increased thereby.
- (ii.) A cross-magnetising action which alternately strengthens the flux at the trailing ($n's'$, Fig. 352) and leading (ns) pole tips, but the former to a greater extent and for longer periods than the latter.

The first of these effects is shown graphically in Fig. 359, which is drawn similarly to Fig. 358, but for a *lead* of 36° , and is to be similarly interpreted. The increase in the average value of the field flux N is very apparent. It is on account of this effect that engineers have advocated

the introduction of condensers into alternate current circuits. The result, as we have previously shown (see pages 545 to 547, Vol. I.), would be to produce leading currents, and therefore to strengthen the fields of the generators by the armature reaction; but the practical difficulty is to produce condensers which will be of sufficient capacity and not break down under the conditions of work. Mr. Swinburne many years ago approached nearest to a solution of this difficulty.

Effects of Hysteresis.—Hysteresis will cause the reversal of magnetic effect to lag somewhat behind the reversal of the ampere-turns in the armature coils, and therefore will usually tend to increase the effect of a lagging current and to diminish the effect of a leading current. The points in which the curves in Figs. 358 and 359 cross the line $F F'$ will be moved a little towards the right.

Characteristics.—The curves of interest to the users of alternators are not quite the same as in the case of self-exciting continuous current dynamos, for it is obvious from the preceding that the curve connecting the P. D. at the terminals with the external current (the "external characteristic" of a continuous current machine) will depend in an alternator not only on the speed and excitation of the machine, but also upon the power factor of the whole circuit, which will be largely influenced by the character of the external circuit. To give the same information as the external characteristic of a continuous current machine (see Fig. 400, Vol. I.), a series of curves would have to be drawn, and before a user could decide which applied to a given load he would have to determine the power factor of that load, not always an easy operation without a special instrument or instruments.

A more useful series of curves would be those connecting the excitation current required to maintain a constant P. D. on the terminals with the machine running at a constant speed from no load to full load for various power factors, though the usefulness of such curves is affected by the consideration just mentioned. The curves, however, would show the amount of regulation required to obtain constant P. D. under different circumstances.

No-Load Characteristics.—A useful and perfectly definite curve for any alternator is the curve connecting the exciting current (or, more strictly, the excitation ampere-turns) with the volts produced at the terminals on open circuit, the machine being run at normal speed during the experiment. Since the dynamo is then quite unloaded, this curve is usually known as the "no-load" characteristic. It is, in fact, the "magnetisation curve" of the machine, for, with no disturbing currents in the armature, the volts generated will appear unaltered at the terminals, and will be strictly proportional to, and a measure of, the useful magnetic flux and the speed, but the latter, being constant, its variation does not affect the curve.

Such a curve for a 3,000-kilowatt two-phase alternator, which may be

taken as fairly typical, is shown in Fig. 360. The general resemblance of the curve to a magnetisation curve can be seen by comparing it with Fig. 252, Vol. I., and especially with the curve for "soft annealed iron" in that figure. Fig. 40 may also be referred to.

Short-Circuit Characteristics.—Another useful alternator curve is obtained by running the machine at normal speed and, with the fields unexcited, short circuiting the terminals through a suitable ammeter. A small excitation current is then passed through the field-magnet coils,

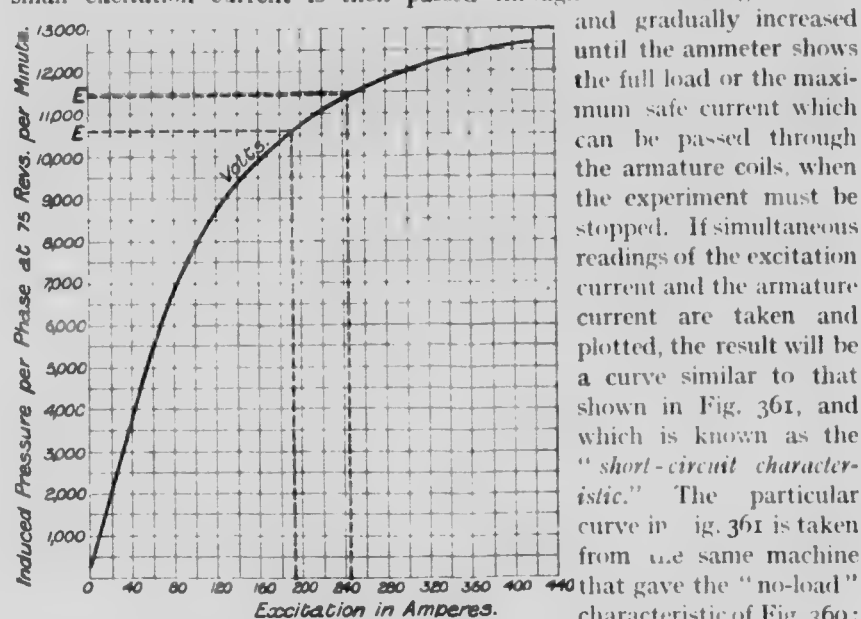


Fig. 360.—"No-Load" Characteristic of a 3,000 K. W. Alternator.

and gradually increased until the ammeter shows the full load or the maximum safe current which can be passed through the armature coils, when the experiment must be stopped. If simultaneous readings of the excitation current and the armature current are taken and plotted, the result will be a curve similar to that shown in Fig. 361, and which is known as the "short-circuit characteristic." The particular curve in Fig. 361 is taken from the same machine that gave the "no-load" characteristic of Fig. 360; and it is interesting to note that the maximum excitation used in the short-circuit experiments is 135 amperes, whilst in the no-load experiments the excitation current was pushed to 420 amperes.

Now this short-circuit excitation is a measure of the inductive reaction of the armature for the various currents considered. For, apart from ohmic resistance, which in this experiment may usually be treated as practically negligible, the E. M. F. due to the field excitation is nearly balanced by the back E. M. F. due to the inductance of the armature under the particular current dealt with. Thus, referring to the above curves, we find that the excitation which gives 150 amperes on the short-circuit curve can set up in the armature coils, as shown by the no-load curve, an E. M. F. of 5,350 volts per phase. To drive this 150 amperes through the ohmic resistance of the armature, which is 0.535 ohm, would only require about

80 volts, whereas 5,350 volts are generated. We may therefore conclude that the short-circuit excitation for any current gives a practical measure of the reactive ampere-turns of the armature for that current. The "no-load" current being practically a wattless current is in quadrature with its E. M. F.

Calculation of Load Excitation.—One use of the "no-load" and "short-circuit" characteristics is to calculate the voltage drop in the alternator under full load, or, what is more important, to calculate the excitation required to maintain a constant P. D. at the terminals when the machine is loaded with any load which it can carry safely. There are several methods of making this latter calculation, but the following, due to Behn-Eschenburg, is simple, and leads to approximately correct results.

It being required to find the excitation necessary to maintain a certain P. D. with a given current load, the excitation (s_1) required to give this current on short circuit is read off from the curve. Also the excitation (s_2) necessary to give the desired P. D. on the unloaded machine is ascertained from the no-load curve. These two excitations added together will give the main part of the excitation wanted. But in adding it must be remembered that the two quantities which are being considered are not in step, and therefore they must be added vectorially, allowance being made for phase difference.

First suppose that the power factor is unity ($\cos \phi = 1$), then the inductive reactance of the armature is in quadrature with the current which is in step with the P. D. at the terminals. Neglecting ohmic drop, this P. D. can only be produced by an impressed E. M. F., which is combined with the reactive volts according to the laws already fully explained (see page 543, Vol. I.). We must therefore set off a line ON (Fig. 362) for the no-load excitation and a line OE at right angles to it for the armature inductive reactance. Measuring s_2 along ON from O and s_1 along OE and joining s_2, s_1 , we find the approximate excitation required for power-factor unity, which will give the necessary effective P. D. at the terminals.

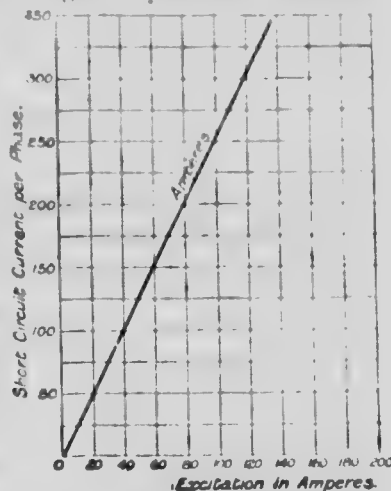


Fig. 361.—Short Circuit Characteristic of a 3,000-K. W. Alternator.



Fig. 362.—Calculation of Excitation (no lag).

For a power factor ($\cos. \phi$) not equal to unity, the current in the armature either lags behind or leads with respect to the E. M. F. by an angle ϕ , and the magnetic reaction on the field flux described above has to be taken into account. In the former case, with the current lagging, we must alter our diagram (Fig. 362) by laying off a line OC (Fig. 363), making an angle ϕ with the line OE , and measure s_1 along this line instead of along OE , because the inductive reactance is still in quadrature with the armature current. The line $s_1 s_2$ will now give the required excitation, and it is obviously of greater length in Fig. 363 than in Fig. 362. In fact, we here

get, in another way, a graphical example of the effect of a lagging current on the excitation of the machine. The effect of a leading current, on the other hand, for which the angle ϕ would be measured on the other or lower side of OE , is obviously to diminish the excitation necessary to produce the required P. D. By marking off the particular value of $s_1 s_2$ * found on the line OC (Fig. 364), the value of the E. M. F., E' , per phase can be found. The load current selected for this example is 75 amperes, and the P. D. 10,000 volts, which is much below the full load.

The above investigation neglects the effect of the armature resistance and eddy currents in increasing the voltage drop, and also assumes that the magnetic leakage is the same for all excitations, which we know is not the case. By assuming that the increase of leakage is proportional to increase of field excitation between no load and full load, a correction can be applied for the change in the magnetic leakage. The eddy current effect is negligible on modern machines, and the effect of armature resistance (R_a)

can be allowed for by calculating the value of the expression

$$\frac{k_a C_a R_a}{\cos. \phi}$$

where the symbols have the usual meanings (see page 331). On adding this to the E. M. F., E' , already found, we get the point E , which requires the excitation to be increased from 192 to 245 amperes.

The above constructions can, of course, be combined in a single diagram, and this has been done in Fig. 365, in which for clearness a heavy overload has been taken, the armature current being assumed to be 400 amperes per phase and the P. D. 10,550 volts. With a power factor of 0.8 this gives an overload of about 50 per cent. The ordinate OX , gives the excitation required to obtain the P. D. ($= OY$) on "no-load." If the

* For clearness Figs. 362 and 363 are drawn to a larger scale than Fig. 364.

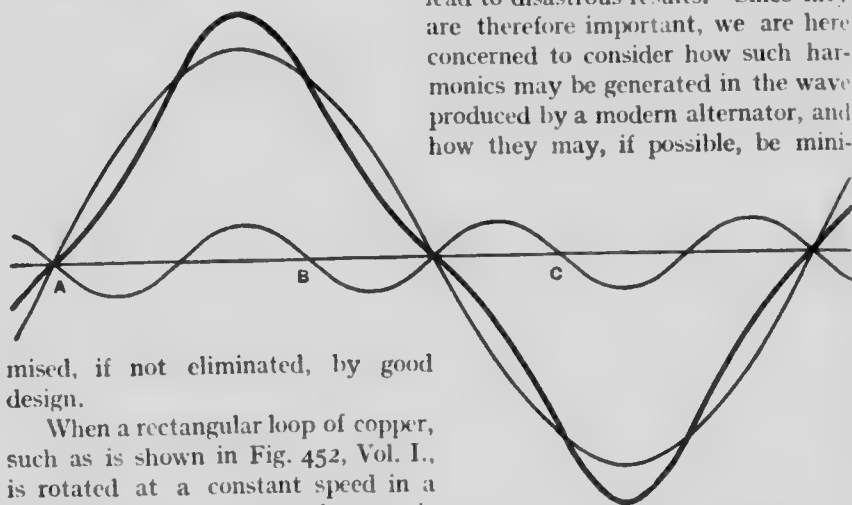


Fig. 363.—Calculation of Excitation (Lag = ϕ).

load is 15.1 per cent., and for the non-inductive load about 9 per cent., which is good regulation when it is remembered that the case worked out is for an excessive overload.

Wave Forms.—Attention has been called (see page 782, Vol. I.) to the necessity for examining the wave form of an alternate current by means of an oscillograph or otherwise to ascertain how far it differs from a simple sine wave. Later, when dealing with the problems of transmission of electrical energy by alternate currents and in other cases, it will be shown that the higher harmonics referred to as being sometimes present may through *resonance* give rise to surgings of currents which may

lead to disastrous results. Since they are therefore important, we are here concerned to consider how such harmonics may be generated in the wave produced by a modern alternator, and how they may, if possible, be mini-



mised, if not eliminated, by good design.

When a rectangular loop of copper, such as is shown in Fig. 452, Vol. I., is rotated at a constant speed in a perfectly uniform horizontal magnetic field, a simple sine wave of E. M. F.,

Fig. 365.—Sine Wave and Third Harmonic.

as shown in Fig. 453, will be generated in the copper in each complete revolution. In other words, the rate of cutting of magnetic lines at each instant will be proportional to the sine of the angle of the position of the loop at the instant as measured from the vertical position. Even, however, in the simple case shown in Fig. 452, it would be difficult to satisfy rigorously the condition that the field should be horizontal and perfectly uniform. With the pole faces as shown, there would be a curving outwards and a slight separation of the lines at the top and bottom of the field, making the rate of cutting less at and near the vertical positions and relatively increasing the rate for the same total flux cut at and near the horizontal position. The effect would be slight, but distinctly perceptible, if the wave form were analysed, being not so marked, but the same in kind as is shown in the black curve in Fig. 366. When analysed, this wave is found to consist of a principal or funda-

mental and simple sine wave, combined with its *third harmonic*, of triple the frequency but of much less amplitude; these waves are shown by the two fine line curves. Attention is called to the positions of the loops of the harmonics at and near the points 0° , 180° , and 360° , as showing the effect of the weakening of the field in the vertical positions of the loop on the E. M. F.'s generated near those positions.

The case of a modern alternator is necessarily more complicated; but because of the fringing of the field at the pole tips we should expect to find amongst the more complex results an effect

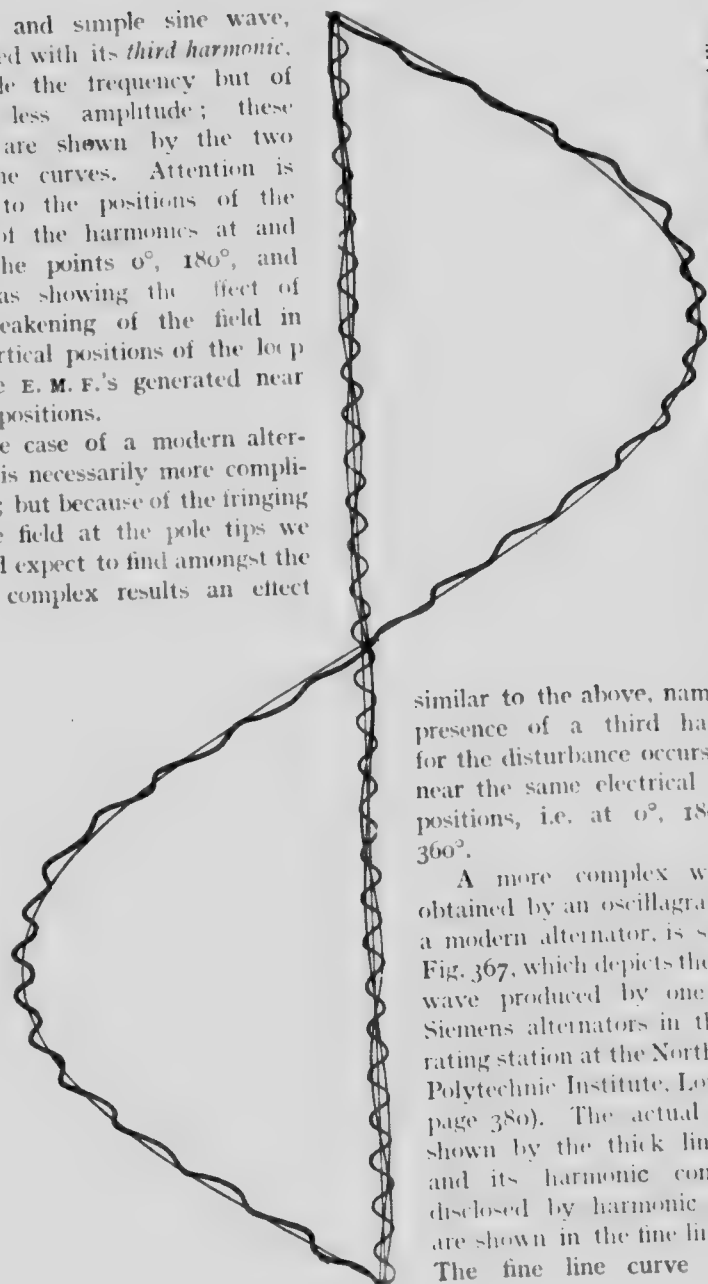


Fig. 367.—Wave Form of Siemens Alternator at 4,400 Volts, into a Fundamental Wave and its Harmonics.

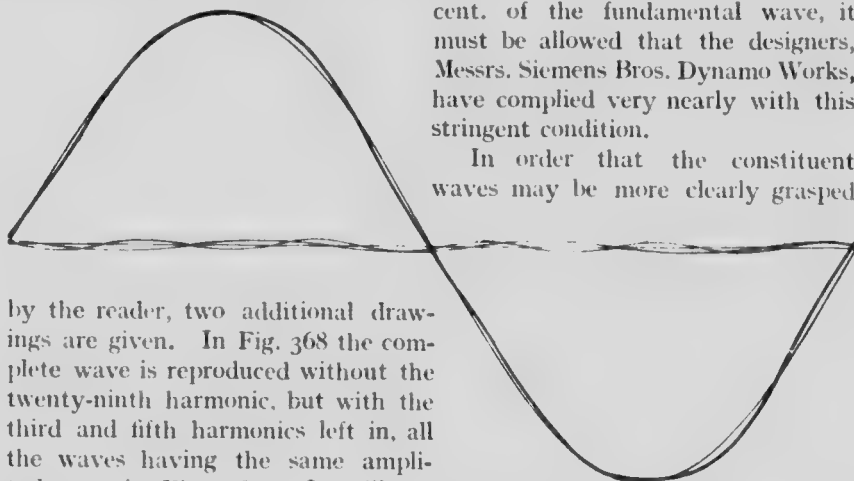
similar to the above, namely the presence of a third harmonic, for the disturbance occurs at and near the same electrical angular positions, i.e. at 0° , 180° , and 360° .

A more complex wave, as obtained by an oscillograph from a modern alternator, is shown in Fig. 367, which depicts the E. M. F. wave produced by one of the Siemens alternators in the generating station at the Northampton Polytechnic Institute, London (see page 380). The actual wave is shown by the thick line curve, and its harmonic constituents disclosed by harmonic analyses are shown in the fine line curves. The fine line curve which is

drawn amongst the ripples of the thick curve is the pure sine curve which most nearly fits the thick curve and represents the main wave of the E. M. F. It will be noticed that in addition to this tonic or fundamental wave no fewer than three harmonics, of sufficient importance to appear in the analyses, are present building up the actual or resultant wave. They are the third, fifth, and twenty-ninth harmonics, and are represented by the curves which lie close to the base line. The curious thing about this particular case is that all the harmonics are nearly of the same amplitude, their amplitudes, in the order named above, being 2.2, 2.3 and 2.5 per cent. of the fundamental wave. As the specification to which the alternator was built laid down that no harmonic was to have an amplitude more than 2 per

cent. of the fundamental wave, it must be allowed that the designers, Messrs. Siemens Bros. Dynamo Works, have complied very nearly with this stringent condition.

In order that the constituent waves may be more clearly grasped



by the reader, two additional drawings are given. In Fig. 368 the complete wave is reproduced without the twenty-ninth harmonic, but with the third and fifth harmonics left in, all the waves having the same amplitudes as in Fig. 367. It will be

Fig. 368.—Curves of Fig. 367 without the Twenty-ninth Harmonic.

noticed that not only do these waves differ from the fundamental in periodicity and amplitude, but that there is also a phase displacement in each case amounting to 218 electrical degrees of lag, or 142 degrees of lead, in the third harmonic, and 163 degrees of lag in the fifth. These phase displacements are the cause of the irregular distribution of the ripples of the resultant wave in Fig. 367 with respect to the pure sine wave.

In order to assist the reader still further, Fig. 369 gives, on a much larger scale, a piece of the central part of Fig. 367, the vertical scale especially being much increased. The relative positions of the harmonic curves with respect to one another can in this diagram be much more clearly made out.

The causes which produce these harmonics are interesting. The third harmonic may be explained in the same way as the third harmonic in Fig. 366, namely by the influence of the pole fringes aided by the radial direction of the

flux in the gap. That its amplitude is so small, and that it is on the whole in the same direction as in Fig. 366, shows that these influences have been very successfully overcome, but that the final result is of the nature of an over-correction.

The fifth harmonic the writer believes to be due to the three-phase grouping of an evenly distributed winding. The curves given are, of course, for one phase only of the winding. In this phase the conductors are in groups covering one-third of each pole pitch. When well under the pole faces, and also when well in the space between the pole tips, this will tend to flatten the curve, as compared with a single-phase grouping evenly distributed, which in a properly distributed field should give the sine curve only or the sine curve with the third harmonic due to the pole tips. The first effect gives rise to a loop opposed to the main loop at or near its maximum, and the second to two opposing loops, one on either side of the zero or crossing point of the main curve.

Except for a small phase difference of 17° due to some secondary cause, this is what the above curves show. As the explanation requires three negative harmonic loops in the half wave, two intermediate positive loops most simply complete the harmonic curve, and there is no reason in this case to expect more.

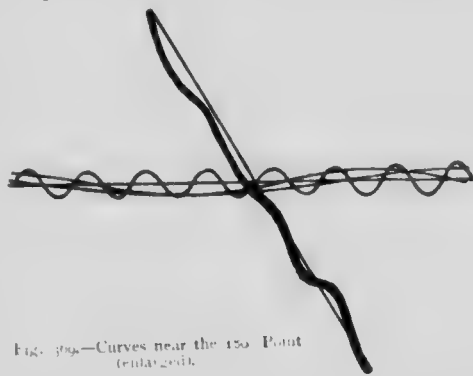


Fig. 369.—Curves near the 150° Point (enlarged).

The twenty-ninth harmonic is not so easy to explain, but the author believes it to be due to the fifteen slots per pole per phase, and to be in reality produced as these slots pass through the leakage field between the poles. It is easy to see that as the teeth pass through this part of the field the reluctance between the pole tips must fluctuate between a maximum and a minimum value. This will cause an oscillation in the spread of the flux, which must set up E. M. F.'s in the armature conductors. For reasons given elsewhere, the harmonics produced must be of an odd, and not of an even, order, and each of the fifteen teeth tends to produce a complete oscillation. Since the conductors are bunched, and there are boundary effects to take into account, the nearest harmonic is the twenty-ninth, since twenty-nine is the nearest odd number below thirty, for it is difficult to see how the periodicity could exceed thirty by one or a small number of periods. It might be objected to the above that since the disturbance giving rise to the oscillation is said to be in the polar gap, it could not be effective throughout the whole wave. It must, however, be remembered that with modern alternators, and when the positions of the leading and trailing

conductors are considered, the fraction of the half wave during which no conductors of the group are in the pole gap is small, and, secondly, that for this interval the oscillations, having been set up, may be expected to persist. This pulsation may be assisted, as Mr. Denton points out, by a synchronous but slight pulsation of the main flux due to the varying reluctance as the teeth and slots sweep past the pole face.

That there can only be *odd harmonics* in the wave form of the E. M. F. of an alternate current generator is easily seen when it is remembered that the disturbing causes which give rise to the harmonics are the same, and

follow one another in the same order for each loop, positive or negative, of the curve. By drawing a few curves with *even* harmonics the student will soon convince himself that these indicate a sequence of changes in *reverse* order, instead of in direct order in suc-

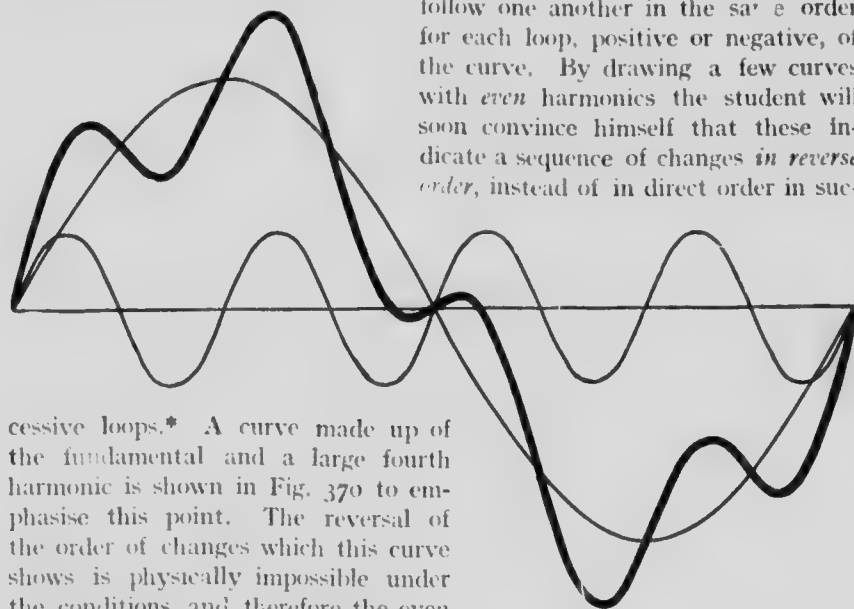


Fig. 370.—Sine Wave and Fourth Harmonic.

cessive loops.* A curve made up of the fundamental and a large fourth harmonic is shown in Fig. 370 to emphasise this point. The reversal of the order of changes which this curve shows is physically impossible under the conditions, and therefore the even harmonics cannot be generated.

The order of the harmonic due to a particular disturbing factor can usually be calculated by the simple rule that it is $(2n - 1)$, where n is equal to the number of disturbing causes in each pole pitch. The three cases given above all conform to this rule.

Connections of Three-Phase Machines.—The existence of the harmonics just referred to has an important influence upon the scheme of winding of three-phase machines, so much so that the "mesh" method of connection is now never used in large- and high-voltage machines of this type, which are always "star"-connected. These two methods of connection for the simple case of a bipolar machine were explained diagrammatically in Figs. 524 and 525 of Vol. I. The very simple cases there given,

* The term *loop* is always used by the author to indicate a half wave.

however, are not the proper analogues of multipolar winding, since with them, the full utilisation of the winding space, the importance of which has been pointed out above (*see pages 300 et seq.*), could not be secured. Instead of there being three coils, one for each phase in the double-pole span, there must be six connected alternately in reverse order, as shown for one of the phases in Fig. 310.

The corresponding bipolar figures, which are analogous to the multipolar case, are given in Figs. 371 and 372 for "star" and "mesh" windings respectively. The six coils shown in each figure could, of course, be made between them to cover the whole periphery of the armature, but for clearness, intervening gaps have been left. Each phase, it will be noticed, consists of two coils, A and A₁, B and B₁, C and C₁, 180 degrees apart, joined in series, but with the connections of one of the coils reversed.

In Fig. 371 three of the six terminals are joined to J, the junction or neutral point, and the other three are the terminals of the machine. The directions of the currents at the instant are shown by arrow-heads on the wires, two of the phases giving currents away from J and out from the machine, whilst the other phase carries an inward flowing current.

In Fig. 372 the three groups are "mesh"-connected, being put electrically in series to form a closed circuit by connecting the end of A₁ with the beginning of B, the end of B₁ with the beginning of C, and the end of C₁ with the beginning of A. From this closed circuit the outer leads a, b, and c are carried off, and it should be noticed that although the electrical positions of the six coils are the same as in Fig. 371, the phases at the instant in the outer circuit are different, one only of the current, being outward, the other two being inwards, it being supposed that

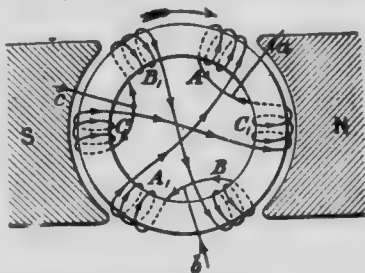


Fig. 372.—"Mesh" Connections of Three-Phase Alternator.

the coils are extended in the direction of the rotation to cover the surface.

Triple-Frequency Circulating Currents.—It is in the last case that it is possible for triple-frequency currents due to the third harmonic to circulate inside the machine in the mesh-connected conductors. To make this clear, Fig. 373 shows the three circuits of the generator separate from one another, with the directions of the E. M. F.s of the main waves and of the

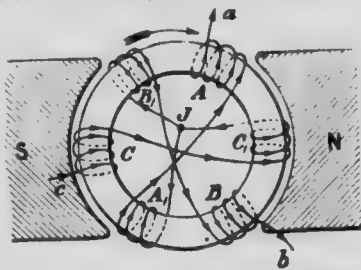


Fig. 371.—"Star" Connections of Three-Phase Alternator.

harmonics indicated by arrows for the instant when the main wave of E. M. F. on phase A has passed its zero point in the upward swing. The ordinates in the A phase would be found in Fig. 366, to the right of the point A. The outside arrow a indicates the direction of the E. M. F. in the main wave, and the inside arrow h_a the direction of the E. M. F. in the third harmonic. These arrows are oppositely directed. In the B phase the ordinates at the instant will be found to the right of the point B in Fig. 366; they are again oppositely directed, as shown by the arrows b and h_b , but are in the same circuital directions as in A. In the c phase, which is formed to the right of c in Fig. 366, both the main wave and the harmonic have negative ordinates; these are indicated by the arrows c and h_c .

If now the ends J be joined, and a_1 , b_1 , and c_1 are taken as terminals, we have the case of Fig. 371. Load currents will flow outwards at a_1 and

b_1 , and inwards at c_1 . The harmonic E. M. F.'s h_a , h_b , and h_c , however, are all directed towards J, and are all equal; they cannot produce any currents, as they have no closed circuits, and their effect is simply to raise the potential of J, which may in certain cases be important as we shall see later.

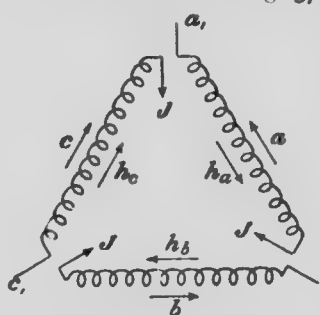


Fig. 371. Triple-Frequency Currents.

The case is different, however, if the b_1 corners be closed, so as to give the "mesh" connections for Fig. 372. In this case the E. M. F.'s h_a , h_b , and h_c are placed electrically in series in a closed circuit, namely the internal circuit of the mesh, and therefore *triple-frequency currents* will flow internally in the armature conductors and will persist; for, by taking any other case, it is easy to see that the E. M. F.'s of the third harmonic are always in series and always in phase in this circuit. The heating effect of these currents obviously reduces the efficiency of the machine. Their high frequency tends to cut down their magnitude through increased inductive reactance, but since there is always one, and sometimes two, opposed to the load current. If the conductors lie close together, the inductance L of the mesh for the currents is less than the sum of the inductances of the three phases for the load currents.

Triple-Frequency Earth Currents.—The effect in the "star" case must not be overlooked simply because it does not give rise to currents in the generator itself. It must be remembered that the third harmonic subjects the junction point J to an alternate sine wave of potential, which may give rise to currents if a separate circuit is provided on the other side of J, either by earthing J or connecting it to the neutral or any other point

of the load circuits. If, therefore, J be earthed, a choking coil should be inserted in the earth connection to kill the triple-frequency currents; if other connections are made appropriate precautions must be taken.

Form Factors.—The *form factor* (see page 783, Vol. I.) of the "Northampton" alternator curve (Fig. 367) is 1.17, which, when compared with the form factor 1.1107 for a true sine curve, is a measure of the departure of the actual curve from the simpler form. As the top value of the ordinates, or, rather, as it may be called, the "peakiness" of the top of the curve, is also of importance, Professor Kapp has proposed that what he calls the "*crest factor*" should be taken into account. This is defined by the equation:—

$$\text{Crest factor} = \frac{C_{\max}}{C_{\text{r.m.s.}}}$$

that is, as the ratio of the value of the maximum ordinate to the root mean square or virtual value of the ordinates for the whole curve. For a sine curve this ratio is 1.414, for the "Northampton" curve it is 1.71.

VII.—EXCITATION AND REGULATION

Excitation.—It is obvious, as has already been pointed out, that the alternate current from an alternator cannot be used directly to furnish the steady, or approximately steady, field required for its field magnets, and that therefore some other method, either entirely independent of, or only indirectly dependent on, the main current produced, must be provided. The methods practically available for providing the field or the current for exciting the field may be briefly summarised as follows:—

- (i.) Permanent steel magnets.
- (ii.) Special coils on the armature connected to a commutator, but only furnishing sufficient continuous current for excitation purposes.
- (iii.) Continuous currents furnished by rotary converters run from the alternate current busbars through step-down transformers if necessary.
- (iv.) Separate exciters for each alternator, these exciters being either directly coupled to or driven by a belt or gearing from the main shaft of the alternator, and each having for its external circuit only the field magnet of the large machine.
- (v.) Entirely separate continuous current plant laid down for the purpose of supplying excitation current to the whole of the alternators in a station.

Of these methods (i.) has long been abandoned for modern machines because of the unwieldiness and great first cost of the permanent magnets which would be required, even for machines of comparatively small output. For comparison the interest on the extra cost of permanent magnets would

have to be set against the waste of energy in the copper losses of the exciting circuits of electro-magnets, but with permanent magnets simple methods of control would be unavailable, and parallel running of several machines impossible.

The second method (ii.) has been used with some success on small machines, but it can only be applied to some types of alternators, and has now been generally abandoned because of the extra complication it introduces in the armature of the principal machine and a want of flexibility in the control.

In regard to the next method (iii.) a difficulty will obviously arise if the station in which it is used becomes entirely "dead"—that is, if all the machines should be stopped at the same time, and there should be no alternate currents available to drive the rotaries. For until the large machines are excited they cannot furnish the necessary current to the rotaries, and until the latter are so driven they cannot furnish the excitation currents to the large machines. The method can therefore only be used where there is a reserve of continuous current energy, in the form, say, of a secondary battery, which can furnish sufficient continuous current to excite at least one alternate current machine, and so start the station running again. Such a battery could be charged by the rotaries during the periods of light load.

The last two methods (iv.) and (v.) are by far the most widely used. Of these (v.) would obviously be used only in generating stations sufficiently large to justify a separate exciting plant, whereas (iv.) can be used in such stations, and also where only one or two large alternators are installed. Both systems have their advocates. On the one hand it is pointed out that with the separate plant—which would usually be connected to a special low-pressure continuous current switchboard—the voltage of all the alternators in the station can be raised or lowered simultaneously, if necessary. Also, that the voltage of an incoming machine can be adjusted to a nicety before it is put on the alternate current busbars, and that the excitation of this will be kept up, and will not be affected by its prime mover feeling the stress of the oncoming load. Further, steady parallel running can be more easily maintained with the separate exciting plant.

On the other hand, trusting the whole of the excitation of a large station to a single dynamo—or even to more than one dynamo—connected to a single switchboard is uncommonly like giving hostages to fortune by putting all your eggs into one basket, to which, if anything happens, nothing but disaster can ensue. Where separate exciters are used with each machine, should anything go wrong with the exciter or the field-magnet circuit of one machine, only that machine need be thrown out until the mischief is remedied. In addition, the separate exciters for each machine are in most cases cheaper, as with special exciting plant additional driving engines have to be provided.

In a number of the illustrations already given the separate exciters driven by the large alternator engines are shown. Thus amongst the slow-speed alternators the following appear with exciters on the main shaft, namely, the Crompton alternator (Plate V. and Fig. 211), the Bruce-Peebles alternator (Plate VI. and Fig. 213), the Holmes-Clayton and Siemens alternators shown on page 224, the Electrical Company's alternator (Fig. 216), and the Mather and Platt alternator (Fig. 235). Some of the turbo-alternators referred to also have their own exciters similarly driven, notwithstanding the

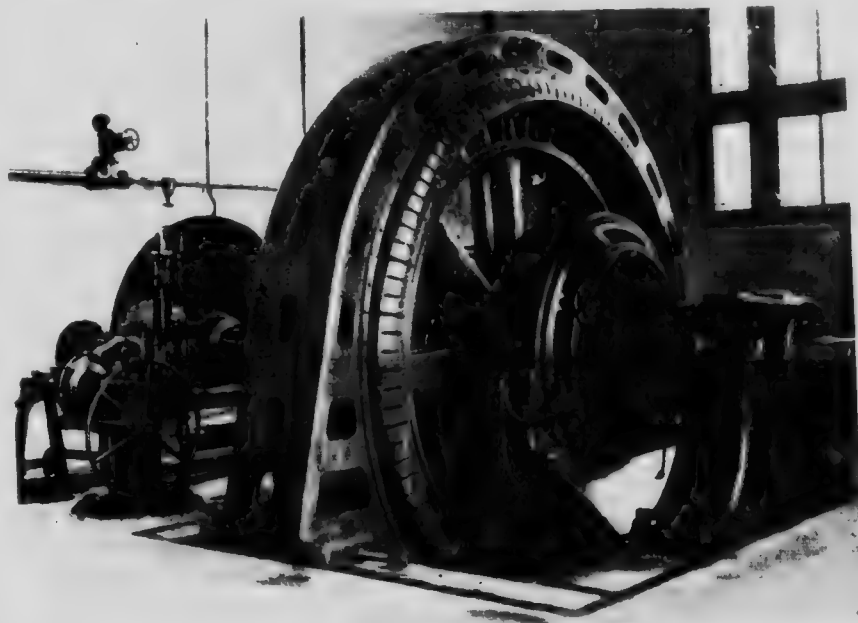


Fig. 374.—Slow-Speed Alternator with Exciter Cased Bearing.

commutator troubles which have to be faced. Reference may be made to the Bruce-Peebles turbo-alternators (Fig. 219) and the Parsons turbo-alternator (Fig. 220). Hydro-alternators often follow the same rule, as will be seen by reference to Brown, Boveri and Co.'s machines in Figs. 257, 259 and 262. Lastly, the Mordey monocoil excitation alternator (Fig. 271) in early days also had its direct-driven exciter, and was, in fact, one of the pioneer machines in this method of obtaining the necessary excitation. The exciter is, of course, not an essential part of these machines, any one of which can be supplied without its exciter for use in a station where special exciting plant is provided.

The above examples illustrate well the variety of methods by which

the mechanical problem of mounting the exciter on the shaft of the large alternator has been solved. In many of these the small exciter, i.e. small in comparison with the alternator, is carried on a bracket built up on, or just outside, the pedestal of the large machine which is remote from the prime mover, though sometimes there is another pedestal on the far side of the continuous current machine.

A position, however, may be found for the exciter inside the outermost pedestal of the alternator as appears in Fig. 374, which shows a generator with its exciter and water-turbine governor as built by the General Electric Company of America. In this case the exciter field is carried on its own bed plate, which is placed between the alternator pedestal and its rotor. The alternator is a 32-pole slow-speed machine with a full load output of 1,800 K. W. at 4,400 volts, and 40 Ω when running at 150 R. P. M. The exciter is an 8-pole continuous current slow-speed dynamo, with a maximum

output capable of supplying the excitation current for the alternator at its full guaranteed overload. The disadvantage of this position for the exciter is that one of the main supports of the heavy rotor is removed much farther from the principal weight to be supported than would be necessary if the exciter were outside the bearing. The diameter of the intervening shaft must therefore be sufficiently large to carry this weight as it passes through the exciter, whereas in the other position a reduced diameter would



Fig. 375.—Collector Rings, General Electric Company.

be sufficient on the other side of the pedestal, as the torque to be transmitted to the armature of the exciter is quite small compared with that required for the rotor of the alternator.

Collector Rings.—It has already been pointed out that the great advantage of rotating the field magnets instead of the armature of a large high-voltage alternator is that only a low-voltage excitation current has to be passed through rubbing contacts. Satisfactory mechanical arrangements for these contacts are not difficult to devise, as the principles involved are fairly simple. It will not therefore be necessary to deal exhaustively with the various excellent arrangements which have been designed, and it will probably suffice in addition to details which have appeared in some of the foregoing illustrations to depict in Fig. 375 the collector rings designed by the General Electric Company of America for their large water-driven slow-speed alternators. The rings in this case are of cast iron, well insulated from one another and from the central hub. All surfaces are well exposed to the air, thus securing good ventilation.

For high-speed turbo-alternators the rings are more usually shrunk

upon the shaft with proper insulation interposed, the method used being more or less similar to that already described (see page 145) for the shrinking of the steel binding rings on the commutators of turbo-dynamos. The rings themselves should be of steel or iron because of the larger coefficient of thermal expansion of copper, but they are sometimes faced with copper for the rubbing surface.

Regulation.—In alternators, as in continuous current machines (see page 177), the passage of a current through the armature affects the P. D. at the terminals by reason of

- (i.) The "lost volts," which are required to drive the current through the ohmic resistance of the armature, and
- (ii.) The "armature reaction," due to the current in the armature producing a magnetic effect which reacts on the field set up by the field magnet.

Since, however, alternators are separately excited, their P. D. is not affected by the third source of disturbance in shunt-wound machines—namely, the diminution of the exciting current due to the fall of the P. D. at the terminals.

By far the more serious of the two above-named causes which contribute to the voltage drop at the terminals of an alternator as the load increases is the armature reaction, which in some alternators is so great that the excitation current required to maintain the P. D. at full load is considerably greater than the current which will give the same P. D. on open circuit. Moreover, as has been shown more fully in the last section, the armature reaction is much greater when the power factor is small than when it is nearly equal to unity; in other words, the "lag" of the current in the circuit becomes of great importance in regard to the regulation.

Inherent Regulation.—Notwithstanding the difficulties imposed by the underlying natural laws and principles, it has been for long one of the objects of designers of alternators to produce machines which should have good "inherent" regulation. To do this it was necessary to work with well-saturated iron or comparatively long air gaps in the magnetic circuit, so that the armature reaction for the load currents and the disturbance caused thereby should be reduced to a minimum. Even then the regulation obtainable is not to be compared with the regulation of a well-compounded continuous current dynamo. The regulation is usually expressed either as (i.) the percentage *drop* in pressure between no load and full load at a given power factor when the load is thrown on, or, (ii.) the percentage *rise* in pressure when the specified full load is suddenly thrown off. For non-inductive loads (power factor = 1) the results usually allowed are from 4 to 6 per cent. for large machines; but for an inductive load with a low power factor, for instance, 0.7, the limit is not below 16 or 18 per cent. In large turbo-alternators

high-flux densities are not desirable, because of the difficulty of getting rid of the hysteric heat, and in these machines 25 per cent. drop or rise in voltage has to be allowed. To attain even these poor results high efficiency and a good output coefficient have to be sacrificed, whilst if a sudden short-circuit occurs on the mains the machine generates far larger and more disastrous currents than if its regulation were still worse. These heavy short-circuit currents have not only been known to damage the windings and disturb the end connections of the alternator (*see* page 319), but cases have occurred where main cables conveying the currents have been wrenched from their supports. It is therefore not surprising that modern practice has developed in the direction of poorer inherent regulation of pressure, and that recourse is being had instead to external pressure regulation. Besides the above reasons the higher inductance of the machines with poor inherent regulation is better for parallel working, as will be shown later.

The above facts lead to the conclusion that in order to maintain the voltage at the terminals of an alternator practically unchanged, either the exciting current in the field magnets must be varied as the load increases and decreases, or the speed of the machine must be varied so as to alter the E. M. F. generated. Of these alternatives the simpler is the alteration of the exciting current, and the chief point to consider is how this may be done most conveniently. A method often used is to vary the exciting current by altering, by hand, resistances in the circuits of the generators which supply the current; but it is obviously more convenient to make the variation automatic and dependent upon the load of the alternator in the same way that the compound winding of continuous current machines automatically increases and decreases the excitation of those machines as the load varies. These two chief methods will now be considered separately.

Hand Regulation.—The control of the current in the field-magnet circuit of the alternator can be effected by altering the resistance of that circuit by means of adjustable resistances such as are illustrated in Figs. 178 to 181. These regulating resistances can be placed at the switchboard close to the voltmeter of the alternator, and the amount of resistance in circuit can be altered according to the reading of the instrument. Such a method requires that at light loads additional resistance shall be introduced into the exciting circuit, and this resistance leads to an increase of the $C^2 R$ loss in that circuit.

A much more economical method is to alter the P. D. of the exciting dynamo, which will usually be either a shunt- or a compound-wound machine, by altering the resistance in its shunt circuit by the method shown diagrammatically in Fig. 177. The resistance, however, is now to be so varied that the P. D. at the terminals of the continuous current

generator rises with the rise of load of the alternator instead of being kept constant, which was the case originally considered in connection with the above figure. In this way the C^2R loss of energy in the exciting circuit of the exciting dynamo at light loads of the alternator will be much less than the corresponding loss in resistances introduced into its main circuit.

This last method of regulation can best be applied when each alternator has its own exciter. Where the whole of the alternators of a large station are being excited from a separate continuous current plant both methods of regulation should be available. The resistances in the exciting circuits of the alternators will be required to adjust their P. D.'s *inter se*, whilst any alteration of resistance in the shunt circuits of the exciting dynamos, assuming these to be properly compounded for constant P. D., will affect the whole of the alternators in the station simultaneously. Suitable rheostats for the regulation under consideration have already been fully described in connection with the regulation of continuous current machines (*loc. cit.*), and we need not therefore pursue this part of the subject further here.

Automatic Regulation.—The automatic control of alternators is not so easy as that of continuous current machines, on account of the exciting current being derived from a source independent of the machine, except that in some cases the exciting dynamo is driven by the same prime mover.

For such cases this fact suggests that the governor of the steam-engine might be electrically controlled by the action of a solenoid actuated by the full P. D. of the alternator, and so set that when the P. D. falls the governor allows the engine speed to increase. This would have a double effect, inasmuch as the exciting current would be increased by the increased speed of the exciter, and the generated E. M. F. would be increased by the increased speed of the alternator. Both these effects would tend to increase the lowered P. D. This method of regulation has been successfully used in the Parsons turbo-alternator, the details of the plan being much the same as for the turbine-driven continuous current machine (*see page 101*). The case is, however, simpler as regards both engine and alternator than the more common case where reciprocating engines and more slowly running alternators are used.

It is also possible with more complicated devices, which have been worked out into practical shape by M. Thury, to cause the P. D. of the alternator, either directly or indirectly, to control the line circuit of a relay (*see page 402, Vol. I.*) in the local circuit, or circuits, of which there are electric motors which are geared to move over the arms of controlling resistances in the manner which has already been described for rocking the brush gear of continuous current dynamos. These resistances being placed either in the field-magnet circuits of the alternators or, better still, in the shunt circuits of the exciting dynamos, can by their insertion or

withdrawal so alter the excitation current of the alternator as to bring back to the normal value the P. D., if and when disturbed by any cause.

All such step-by-step corrections, however, fail to lead to satisfactory practical results, because the change which it is their object to prevent must be allowed to commence, and often to develop more or less, before the correction is applied. Attempts have therefore been made with a very fair measure of success to devise regulators which shall act much more promptly, so much so that the pressure variation which is being corrected

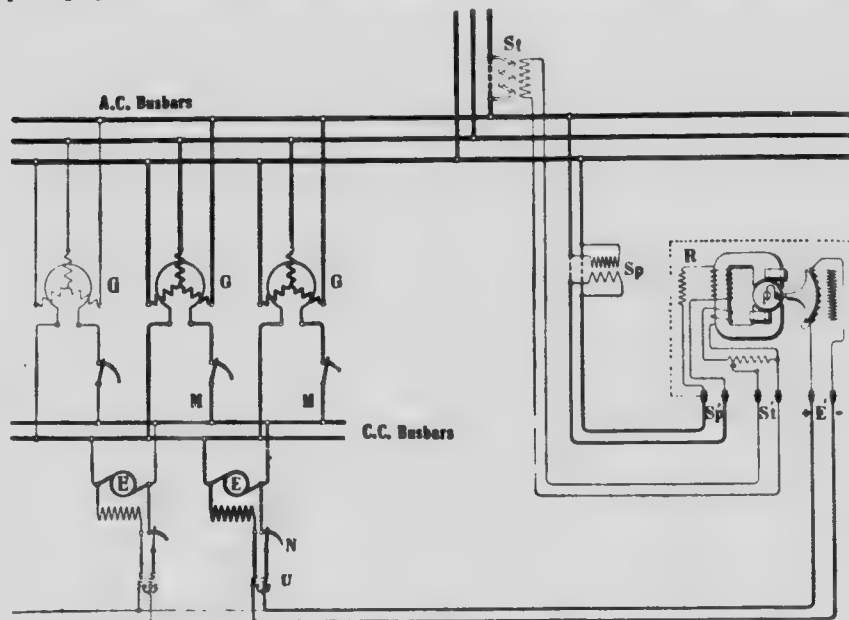


Fig. 376.—Connections of Brown, Boveri's Regulator for Alternators Excited from C.C. Busbars.

is barely perceptible on a station recording voltmeter of ordinary sensitivity.

The Brown, Boveri automatic regulator already fully described (see pages 187 to 190), in connection with the regulation of continuous current machines is also admirably adapted for regulating the pressure at the terminals of alternators. The regulator itself is very similar in the two cases, the only important difference being that a small four-pole single-phase alternate current motor takes the place of the bipolar continuous current motor of Fig. 185. The various mechanical and damping devices (Figs. 186 to 188) are identical.

The connections of the regulator to the circuits of the generator are, *mutatis mutandis*, also the same, and are shown diagrammatically in Fig.

for the case of three alternators G excited from continuous current bus-bars $M M$, which are energised by the C. C. exciter dynamos E . This diagram could be compared with Fig. 185, and the differences noted. The resistance between the terminals E' of the regulator is, as before, in the field circuit of the dynamos, and its variation by the action of the regulator varies the shunt current and, therefore, the P. D. of the exciters. The terminals sp' of the regulator are connected to the phase of one pair of the A. C. bus-bars, either directly if the voltage of the mains be low, or through a step-down potential transformer if the voltage be high, which is the most usual case. Finally the terminals st' of the regulator are connected to the secondary of a step-up current transformer st whose primary is in one of the mains carrying the load current. With these connections the action is the same as in the case previously described.

If the alternators are excited, each by its own exciter, the shunt circuits of these exciters are placed in parallel on the terminals E' of the regulator, but in this case the alternators and their exciters must be similar machines.

Another automatic regulator which is widely used for both continuous and alternate current work is the Tirrill regulator, manufactured by the British Thomson-Houston Company in England and by the General Electric Company in America. The main principle used in this regulator is the automatic throwing in and out of circuit of a single

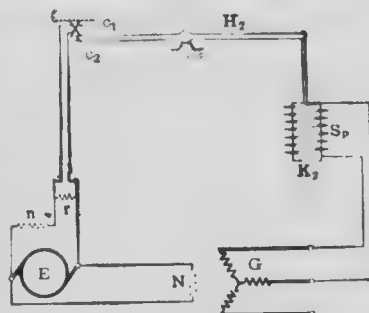


Fig. 377.—Main Principle of the Tirrill Regulator.

theostatic resistance, which is in the shunt circuit of the exciter. By properly designing the exciter and proportioning this resistance it is possible to vary the voltage of the exciter quickly through a wide range, say from 125 volts to 25 volts in a few seconds. This device, however, by itself would lead to hunting, and be of no practical use, were it not used in conjunction with another device called by Seidner the "back control," the chief effect of which is to hand over the completion of the regulation, and the control of the range through which the alteration of the exciter pressure shall be allowed to vary to another piece of automatic mechanism usually referred to as the "exciter control magnet."

The main principle of the regulator is shown diagrammatically in Fig. 377, and with the principle of the "back control" added in Fig. 378, in both figures, which are taken from a paper by Seidner.* For clearness the auxiliary electrical and mechanical additions necessary for successful working are omitted. In Fig. 377 a balanced lever H_2 carries at one end the

* *Electrician*, Vol. LXV., page 56 (1910).

core K_2 of an electro-magnet sp , which is energised by a voltmeter current from one of the phases of the alternate current generator G . At the other end of the lever are contact pieces c_1 and c_2 which, when in contact short-circuit the resistance r , which is in the shunt excitation circuit of the exciter dynamo E .

Assuming that the contacts at c are open when the P. D. of the generator is normal, if that P. D. rises beyond a prearranged limit the core K_2 of the electro-magnet will be lifted, and the contact at c opened, throwing the resistance r into the field-magnet circuit of the exciter E . The voltage of the exciter immediately begins to fall, and with it the excitation current supplied to the field magnet N of the generator, whose voltage in its turn also begins to fall until such time as the electro-magnet allows the core K_2 to fall back to its normal position, when the contact at c again closes

and the resistance r is again short circuited. The exciter voltage will then cease falling, and with it the current in N , and the fall of the P. D. of the generator will be stopped.

Now because of the time taken to perform the first part of the above cycle, in consequence of the inertia, both magnetic and mechanical, of the various parts of the apparatus, it is quite certain

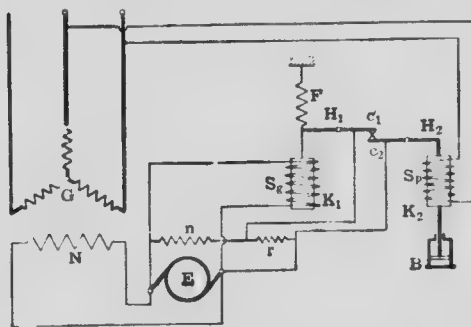


Fig. 378.—The Tirrill Regulator, with "Back Control."

that in this simple form there would be "over-correction," that is, the P. D. of the generator would sink too low before the contacts at c were closed, and in coming back to the normal, the P. D. would again overshoot the mark and rise, perhaps, considerably before the downward movement of K_2 could be arrested and the contacts again opened. In certain cases dangerously large oscillations, technically known as "hunting," might thus be set up, and the interposition of the regulator lead to disaster instead of safety.

It is to prevent this "hunting" that the "back control" shown in Fig. 378 is introduced. A second balanced lever H_1 , carrying the contact c_1 at one end alters as may be necessary the actual position of the contact at c . This lever is controlled by the core K_1 of the electro-magnet sg , and the tension of the spring F which acts against the weight of the core K_2 and the downward pull of the electro-magnet. The pull of the electro-magnet depends upon the P. D. of the exciter E across whose brushes its coil is bridged. As soon as this P. D. begins to fall on the cycle of operations previously described the downward pull of sg on K_1 is relaxed, and if

the tension of F , which can of course be adjusted to any required value, be sufficient, the left-hand end of the lever H_1 is raised, and the contact C_1 depressed, thus closing the short circuit on r before the P. D. of E or of G has altered very much. If the P. D. of G is still too high the lever H_1 will again open the contact, which will again be closed by H_1 and so on, until a balance is attained. The wide changes of P. D., both of E and G , which would be possible under the simpler arrangement of Fig. 377 are now prevented, and "hunting" is rendered impossible. The adjustments can be made so accurately that the difference in the positions of the contacts at C between full load and no load due to the movement of the lever H_1 is less than $\frac{1}{15}$ th of an inch, and the path of a single swing of the end of the lever is about $\frac{1}{300}$ th of an inch. The number of swings per minute of the lever D when the voltage is changing varies between 400 and 1,000, so rapid is the action of the various parts of the regulator.

In actual practice the contacts C_1 and C_2 are not used directly to throw the resistance r in and out of circuit, but act indirectly through

a differentially wound relay whose armature acts through a longer distance; the sparking at this contact which would soon burn up the contact faces is killed by the bridging of the gap by a condenser whose mode of action in such cases has already been explained (see page 432, Vol. I.).

The circuits of an actual regulator with the auxiliary electrical and mechanical additions as arranged to control a three-phase generator are shown in Fig. 379, which should be carefully compared with Fig. 378. On the main lever H_2 a counter weight w balances the weight of the core of the main-control magnet combined with the constant pull of the magnet under normal conditions on the exciter-control lever H_1 . The exciter lever H_1 has the weight of the core and the pull of the magnet balanced by four springs F , which are set to pick up successively with a change of 25 per cent. in the exciter voltage, as the exciter voltage required by the alternator at full load and at no load may be in the ratio of two to one. The rheostat

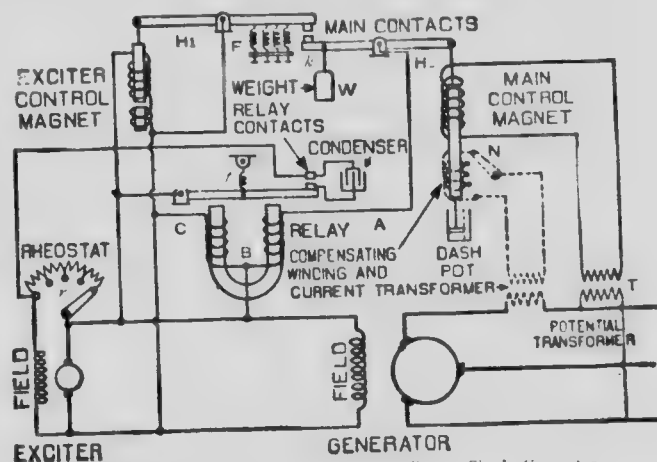


Fig. 379.—Circuits of Tirill Regulator Controlling a Single Generator.

resistance r in the exciter field circuit can be adjusted by hand to various values, and is usually so set that the adding of this resistance would reduce the exciter voltage to about 65 per cent. of its normal value. This resistance is thrown in and out of circuit, not by the main contacts as in Fig. 378, but by the relay contacts which are also bridged by a condenser as explained above. The resistance is out of circuit when these contacts are closed, and in circuit when they are opened. The contacts are operated by the armature of the "relay" magnet, the pull of the magnet acting against



Fig. 380.—Turrill Alternating Current Regulator, with One Relay.

the spring f . The magnet is wound differentially; one half of the winding is always receiving current direct from the exciter terminals, whilst the other half only receives current when the "main contacts" are closed. As the two currents act against one another the armature is attracted and the relay contacts opened only when one of the currents is suppressed by the opening of the main contact. The action is therefore the same as in Fig. 378, namely that the resistance r is thrown into the exciter field circuit when the main contact is opened. The opening and closing of this latter contact depends as in Fig. 378 on the interplay of the exciter control and main control magnets. The former of these is connected as in Fig. 378 across the brushes of the exciter, the only difference being that the core is cut

in two, the upper only being movable and attached to the lever H_1 . On the other side the main control magnet has both a shunt and a series winding. The former receives current from a potential transformer T , bridged across one of the phases of the generator, and so connected that when the potential rises, the pull of the magnet is relaxed and the main contacts opened. The series coil on the other hand receives current from a current transformer whose primary is in one of the mains of the generator. In this case the connections are such that as the load current increases the pull on the coil of the magnet increases, tending to keep the main contacts of the regulator closed, thus maintaining the voltage of the exciter. As the electro-

magnetic pulls on this core may change rapidly, a dash-pot is added to make the actual movement of the core sluggish. The number of turns of the series coil can be adjusted by the sliding contact shown at *x*, so that the result may be the same as in an over-compounded c.c. dynamo, namely a rise of voltage at the terminal of the generator as the load increases, in order that the voltage at a distant point may be kept constant.

The actual regulator is shown in Fig. 380, in which the electro-magnets, levers, contacts, etc., appear protected by a glass case. The main control magnet and the exciter control magnet are on the upper part of the panel, on the left and right hand respectively, with the main contacts between them. The relay magnet is lower down and in the middle of the panel.

When more than one exciter is used, as in Fig. 376, it is desirable, in order to allow for the different characteristics of the exciters, to apply a relay magnet for each exciter, but the main control coil and the exciter control coil, bridged in this case across the exciter busbars, will govern any number of relays and exciters.

For this purpose an ingeniously designed multiple relay magnet is used. Its general appearance can be gathered from Fig. 381, where one of these magnets, controlling seven relays, is shown inside the lower part of the case; they are constructed to take as many as twelve relays if required. A diagram of the connections with some of the details of construction is given in Fig. 382. Two

large circular coils *xx* and *yy*, each wound to a distinct circuit, are arranged parallel to one another, and at such a distance apart that **E**-shaped stampings of iron *nsn* can be inserted as shown and built up to form the cores of a number of three-pole electro-magnets, which can be energised by currents in the coils. Only two of these magnet cores, opposite to one another, are shown in the diagram, but their relative positions round the coils will be gathered from an inspection of Fig. 381. Each set of triple poles has facing it a soft iron armature *M* forming one arm of a ball-crank lever pivoted at *p*, and carrying at its upper end at

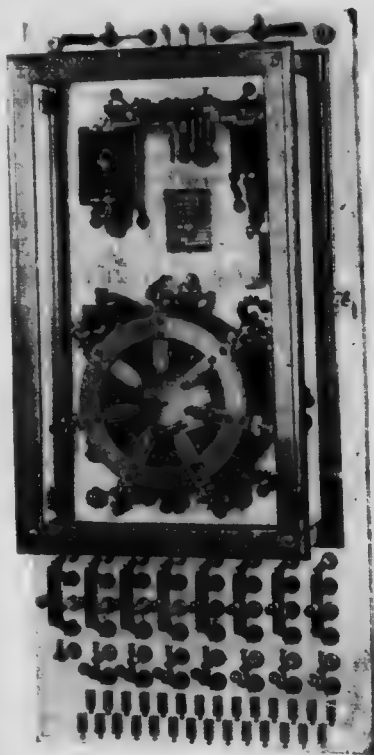


Fig. 381. —Tirrell Regulator, with Seven Relays.

κ the movable contact facing the fixed contact of the relay, carried on the post s . When the magnet cores are unmagnetised the contacts are held together by the springs s pulling on the other arm of the bell crank lever. The tensions of these springs can be adjusted by the screws $w w$.

The terminals of the coil circuits are shown at A, B, and C. A and B are connected to the bus-bars and A and C to the main contacts k of Fig. 379, in which also the letters A, B, and C indicate the corresponding points. The circuits of each coil are joined up as shown for the U-shaped relay of

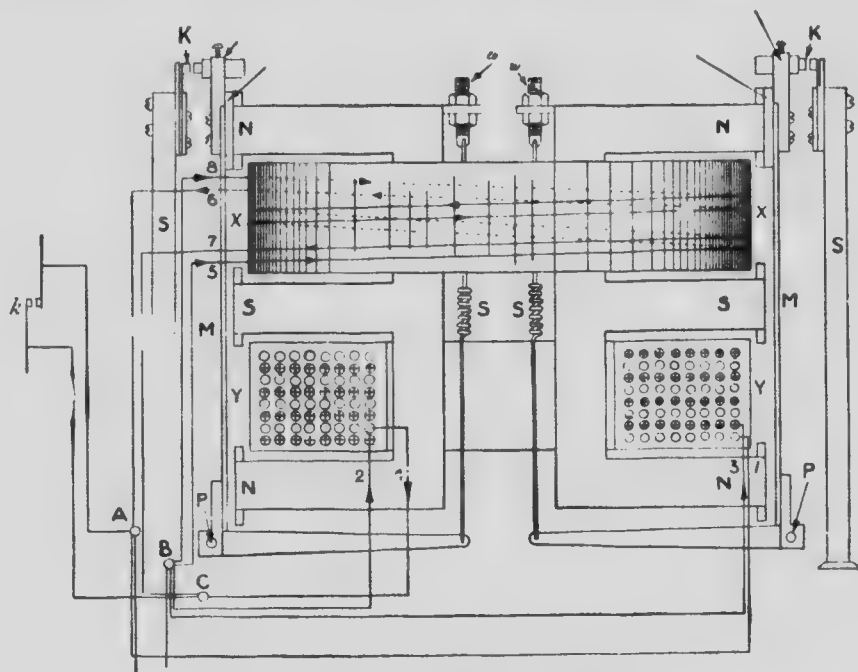


Fig. 382.—Multiple Relay Magnet for Tirrill Regulator.

Fig. 379, so as to act differentially. When the main contacts are closed they are all in parallel with the currents in the A B circuits opposing the currents in the B C circuits. But when the main contacts k open the terminal, A is thrown out of circuit and the coils A B become dead, so that the magnet cores are all energised and the relay contacts are all opened, each throwing its proper rheostatic resistance (see Fig. 379) into the field circuit of its own exciter. The terminals shown below the glass case in Fig. 381 are the connections for the rheostatic resistances of the various exciters, the other terminals being as in Fig. 380.

Just as the Brown, Boveri regulator which we described fully in connection with continuous current work, can be used with proper modifica-

tions for alternators, so the Tirrill regulator, described above as applied to an alternator, can be and is quite readily adaptable for continuous current working.

The weakness of all these automatic regulators for central station work is that they only work well when the generators in parallel are similar machines. Moreover it is not possible for the regulators to act in parallel with one another on different sections of the same station, and therefore a large station must be governed by a single regulator which necessitates the same type and size of machines throughout.

One way of getting over the difficulty where there are dissimilar machines, such as turbo-alternators and slow-speed alternators, in the same station is to regulate the bus-bar pressure by using an automatic regulator for one machine only. For this purpose the turbo-alternator with its large overload capacity of both engine and generator is the better for taking up all the peaks of the load and carrying them with constant pressure with the aid of the regulator.

Compounding.—Several methods of automatic control have been proposed and put into practice which are analogous to the compound winding of continuous current machines, inasmuch as they rely upon the increase of the main

current of the alternator to regulate automatically the excitation of the field magnets. In theory, the simplest method of compounding is to use either as a correcting current or for the whole excitation rectified currents drawn from the alternator itself, either from its ordinary circuits or from special windings on the armature designed for this purpose. The weakness of all these methods is the difficulty of designing a synchronous rectifier free from sparking troubles, and though many ingenious devices have been employed from time to time for this purpose the problem cannot be said to have been successfully solved.

Better methods are those which employ either for the whole or the correcting portion of the excitation the principle of the rotary converter. One of the simplest of these, applicable most readily to polyphase generators, is the following, used by the General Electric Company of America.*

* *The Electrical Review*, Vol. XLIX. (1901), page 344.

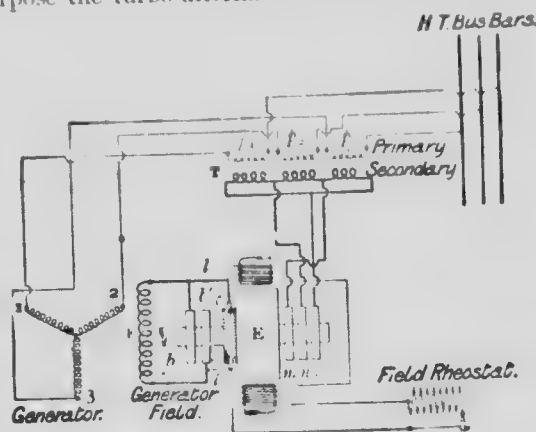


Fig. 383.—Compounding a Three-Phase Alternator.

The three-phase alternator (Fig. 383), which has a revolving field and a fixed armature, has its exciter *E* coupled on the same shaft. The exciter is multipolar, and has the same number of poles as the alternator, the field-magnet circuit of which it supplies with current from its commutator *cc'* by means of the leads *ll'* and the slip rings and brushes *bb'*. Only two of the poles of the exciter are shown. The line currents of the alternator are led from the terminals 1, 2, and 3 of the machine through the primary coils p_1 , p_2 , p_3 of a three-phase series transformer *T* from the mesh-connected secondaries, of which the induced currents are led to three slip rings *m*, *n* and *o* on the shaft of the exciter. These slip rings are joined to points on the armature of the exciter, differing in phase by one-third of a period, and so selected that when the currents in the alternator are in step with the E. M. F. (power factor = 1) these additional currents both strengthen the field of the exciter by their magnetic action and increase the supply of current to the alternator field, the exciting dynamo acting

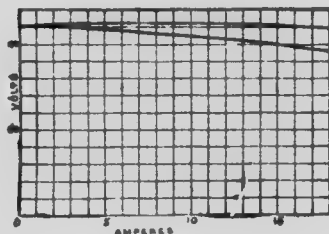


Fig. 384.

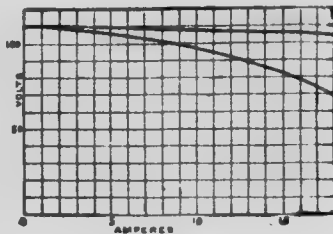


Fig. 385.

Results of Experiments on a Compounded Alternator.

in regard to these currents as a rotary converter (see page 635, Vol. I.). When, however, the power factor of the alternator diminishes through an inductive load and the currents in the coils p_1 , p_2 , and p_3 lag in phase, both the above actions are increased and still more current is supplied to the field, and the increased drop in volts due to the lag is compensated.

The necessary synchronism between the changes in the alternator and in the exciter is attained by both machines having the same number of poles and being coupled on the same shaft. This secures that the field set up by the additional alternate current in the armature of the exciter is fixed in space relatively to the poles of the field magnet, and only alters its position for a new one when the phase of the alternate current changes. For, if the armature of the exciter were stationary, the three-phase currents would give a field revolving with the angular velocity of the alternator. If now the armature of the exciter revolve in the opposite direction with the same angular velocity, the field produced by the three-phase currents will be fixed in space.

A similar method was devised in 1898 by Danielson of Stockholm, the

chief differences being (i.) that he used a *series-wound* exciter on the shaft of the alternator, and (ii) that instead of using the exciter as a rotary converter he wound a supplementary circuit on its armature connected to slip rings (as above), and relied entirely on the magnetic action of this circuit to give the initial strengthening of the field as the load on the alternator increased. As already remarked, the field due to this current will have a fixed position in space for each power factor in the main circuit, and therefore can be made to compensate for all changes of the load in magnitude and phase.

The results of experiments on a machine regulated in this way are given in Figs. 384 and 385. The curves in Fig. 384 are for the case of the alternator running upon a non-inductive load; the lower curve gives the characteristic when the regulating device is not used, and shows a voltage drop of 7 per cent., whilst the upper curve is the characteristic when the regulating circuits are used. The latter curve is very like the curve of a compounded continuous current machine. In Fig. 385 the machine is running on a circuit with a power factor of 0.8; the lower curve (unregulated characteristic) shows a voltage drop from 110 to 70 volts, whilst the upper curve (the regulated characteristic) shows a drop of 6 per cent. only.

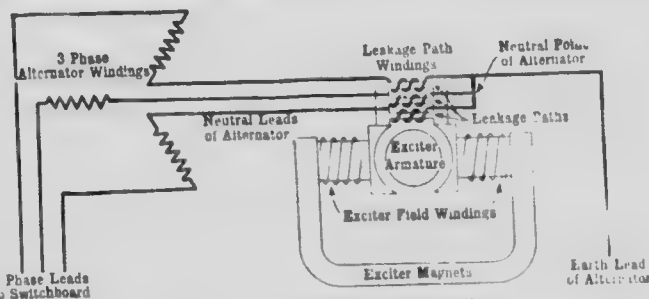


Fig. 386.—Parsons Alternator Compounding.

Other methods which have been worked out seek to increase the field of the exciter by the action of the load current of the alternator. One of the most ingenious of these is shown diagrammatically in Fig. 386. The windings of a star-connected three-phase alternator have the neutral ends of their coils brought out for the purpose of interposing between the neutral point and the alternator the regulating device on the exciter. The exciter is provided with a heavy magnetic shunt or leakage path across its polar horns, so heavy that a considerable fraction of the total flux passes through the shunt, which consists of three cores in parallel so proportioned that at normal excitation of the machine the flux through them is near the saturation flux.

If now these cores be wound with coils through which alternate currents are passed, these currents, when flowing so as to tend to increase the flux already present cannot produce much effect, since the iron is nearly

saturated. When, however, they pass in the opposite or demagnetising direction they can produce a very large effect and by thus, as it were, damming back the flux due to the field windings they can compel a far larger fraction of this flux to pass through the armature, so increasing the voltage of the exciter, and, therefore, the excitation of the alternator. Thus with increasing load on the alternator the voltage of the exciter and the field current of the alternator and its field flux will increase; in other words there is a true compounding effect similar to that which is obtained with continuous current machines, and it only remains to determine whether the compounding can follow the load with sufficient exactness to be of practical value.

On this latter point the curves given in Fig. 387 contribute experimental evidence. The experiments were made upon a 1,000 K. W. three-phase Parsons' turbo-alternator designed for a normal pressure of 3,300 volts between

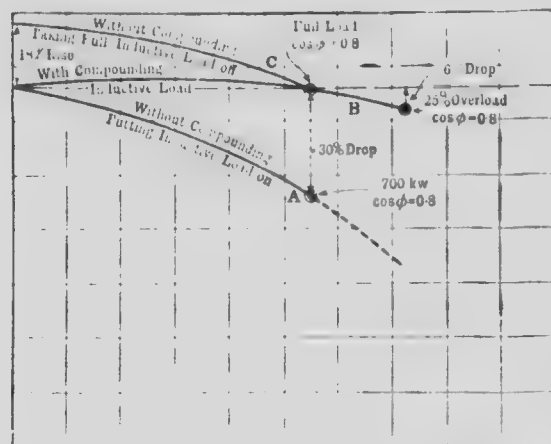


FIG. 387.—Tests on Alternator with Parsons Compounding.

phases, the full load current being 220 amperes per phase when the power factor is 0.8. The curve A shows that without compounding there is a drop of 30 per cent. in the pressure at full-load if an inductive load with the above power factor is thrown on without the excitation being altered, and the curve C shows that when the same load is thrown off after the excitation has been increased so as to restore the normal P. D., there is a rise of 18 per cent. at full load if the increased excitation be maintained. These figures may be taken as a measure of the "inherent" regulation of the machine under experiment. When, however, the compounding device is in circuit the result is that given by the curve B, which shows that the compounding was perfect at full load current, and that the machine was slightly over-compounded for smaller loads. Further, with 25 per cent. overload the terminal pressure only fell 6 per cent., which may be regarded as fairly satisfactory. It is not stated whether the same arrangement would give the proper result with a non-inductive load, for which very likely some adjustment of the ampere-turns on the leakage paths would be required. This is obvious when it is noted that the correction depends upon the magnitude, and

is not affected by the phase of the current. The above machine would therefore probably be over-compounded at full load for higher power-factors up to unity.

Leblanc and others have proposed methods of compounding for alternators, and methods similar to that shown in Fig. 383 have been designed by Reist, Blondel, and others. The examples given, however, are sufficient to show that the problem is within the range of practical solution.

CHAPTER III

GENERATING STATIONS

I.—INTRODUCTORY

THE two preceding chapters having dealt with the principles underlying the construction of electric generators for the supply of electric energy in the form of either continuous or alternating currents, and also somewhat minutely with the details of the construction of such generators, the present chapter will be devoted to the consideration of the problems involved in the utilisation of these machines for the generation of the large or small quantities of electric energy which may be required for public or private purposes. This will necessarily involve the description of the very interesting generating stations which now form such an important feature of modern civilisation, and also of the ingenious and fascinating apparatus and methods used in these stations, including the switchboards, which are so attractive and mysterious to the casual visitor.

It has already been pointed out that the "most conspicuous trend of the developments of recent years has been the tendency to concentrate the generation of electrical power in large stations," and it has been inferred that the choice of the position of the station is in the first instance largely controlled by the predominance in the main problem of the importance of one of two considerations; that is to say, either (i.) the source, be it waterfall, coalfield, or other source, from which the energy is to be obtained, or (ii.) the area of utilisation and the distribution of the consumers who are expected to make use of the energy when ready to be placed at their disposal. If, on the one hand, a new industry or series of new industries is being started, and a source of energy exists in a place easily accessible, the generating station may be placed as close as possible to the source, and the factories or works for its utilisation will gather round the station as its customers. At the other end of the scale there is the case of old-established factories and workshops using other methods for obtaining the necessary energy for their daily work, but far removed from any natural supply of such energy, and who can only be induced to use electric energy if it can be supplied at a cheaper rate. In this case the best position for the generating station may be, though not necessarily, close to the consumers. A special but widely occurring variety

of this case is where the energy is chiefly used for domestic, business, and public lighting purposes.

In the early days of the development of the utilisation of electric power, in which the utilisation was mainly in the direction of electric lighting, it was almost inevitable that the generating stations should be placed sometimes on the outskirts, but also quite frequently in the midst of great urban districts, notwithstanding the fact that land is costly both to acquire and to retain in such a position. As, however, the methods of transmitting and transforming large quantities of electric energy became more fully worked out in detail and systematised, these urban stations began to be superseded by stations placed at some distance from the consumers, where either the sources of energy were more accessible or where the necessary space could be obtained more cheaply, both as regards capital outlay and as regards maintenance charges in the shape of rates, taxes, etc. This process of supersession is still in active operation, the tendency being for individual generating stations to handle far larger quantities of energy than was thought possible in the early days, and to transmit this energy electrically over greater and greater distances to their customers. Quite frequently the older generating stations have been turned into sub-stations, in which the energy is received as electric energy from a more or less distant generating station and distributed electrically to the customers in the vicinity, being transformed in the sub-station to the particular kind of electric energy which is most suitable for the needs of the district.

The development of these large generating stations, handling and distributing enormous quantities of energy, has not, however, superseded the use, in special circumstances, of comparatively small self-contained generating plants. On the contrary, as the knowledge of the advantages of the use of electricity not only for lighting purposes, but also for distributing small quantities of power, has become more widely diffused, and the necessary utilising appliances have been devised and manufactured on an ever-increasing scale, it has been found more and more desirable to have a supply of electric power available. Where, therefore, such a supply is not obtainable from a public generating station, many cases have arisen in which it is both easy and economical to put down special generating plant. It also sometimes happens that even where public mains are not difficult of access, the circumstances may be such as to make it more economical or more desirable to install separate generating plant. This is specially the case in large factories and works, though the advantages of separate generation, even in such cases, tend to become less and less as time goes on, except where there are available sources of power which would otherwise be wasted, such as blast-furnace gas, large quantities of exhaust low-pressure steam, etc.

It is difficult to draw the line at the point at which the term generating

"station" may properly be used. The output of a particular installation may, of course, vary from that required to light a small country house to that which can supply a large industrial and residential area with all the electric power it may require. For our present purpose we propose to exclude from this chapter installations of the smallest type, which will be more conveniently referred to when dealing with "Electric Lighting," for which they are the most usually employed. The term "station" could scarcely be applied to such installations, but should more properly be confined to cases in which there are two or more generators which can be run together or singly, and although this may not be made a hard-and-fast rule, the present chapter will deal only with such cases, except when some particular industrial application requires not more than a single large generator. In other words, it is the industrial and public aspects of the generation of electric power which are being considered as distinct from the domestic aspects.

A further division, however, will be convenient as between those "stations" which are primarily generating stations for the sale of electric power and those where other undertakings—such as mining, shipbuilding, etc.—are the main occupations of the owners, and in which the electric generating stations are adjuncts or ancillary only. The case of generating stations for electric railways and tramways lies between the two, and will be treated with the first-named as being more nearly akin to that.

Before, however, dealing with either type of station, it will not be inappropriate to consider briefly the sources from which the engineer can obtain supplies of energy for his various purposes.

Sources of Energy Available.—It is, of course, understood, when we speak of generating stations, that energy is not "generated" in those stations, for such generation is beyond the power of man to accomplish, so far as our knowledge of natural laws at present extends. This has been more than once referred to in these pages (see especially Vol. I., pages 151, 517, 572, and elsewhere). All that we can do is to transform one form of energy into another, there being always an element of loss in the process by some of the energy taking a form in which it is useless to us. For as we cannot create, neither can we destroy energy, though we may degrade it, as it were, by rendering it unavailable for any useful process with which we are acquainted.

Our "generating" stations are therefore, more strictly speaking, merely "transforming" stations, but as we usually employ the latter word in another connection—namely, for transforming one form of electric energy into another form of electric energy—we shall continue to use the term "generating stations" for stations in which energy is transformed from some non-electric form into one of the electric forms of energy.

This being premised, it is important to ascertain, from among the

protean forms in which energy can appear, what stores of energy exist which are important to the engineer, and it is somewhat startling to find that they can be summed up in a few words. They are the "*energy of fuel*" and the gravitational "*energy of water*" which has been raised above the sea level, or some lower level, to which it can be returned. The energy of fuel is the chemical energy of the separated elements, the carbon and hydrogen of the fuel on the one hand, and the oxygen of the air on the other. The source of this energy can be traced back to the sun, which is also the agent whose energy raises the water from the bed of the ocean to the hills, enabling engineers to utilise its gravitational energy as it returns to the lower level.

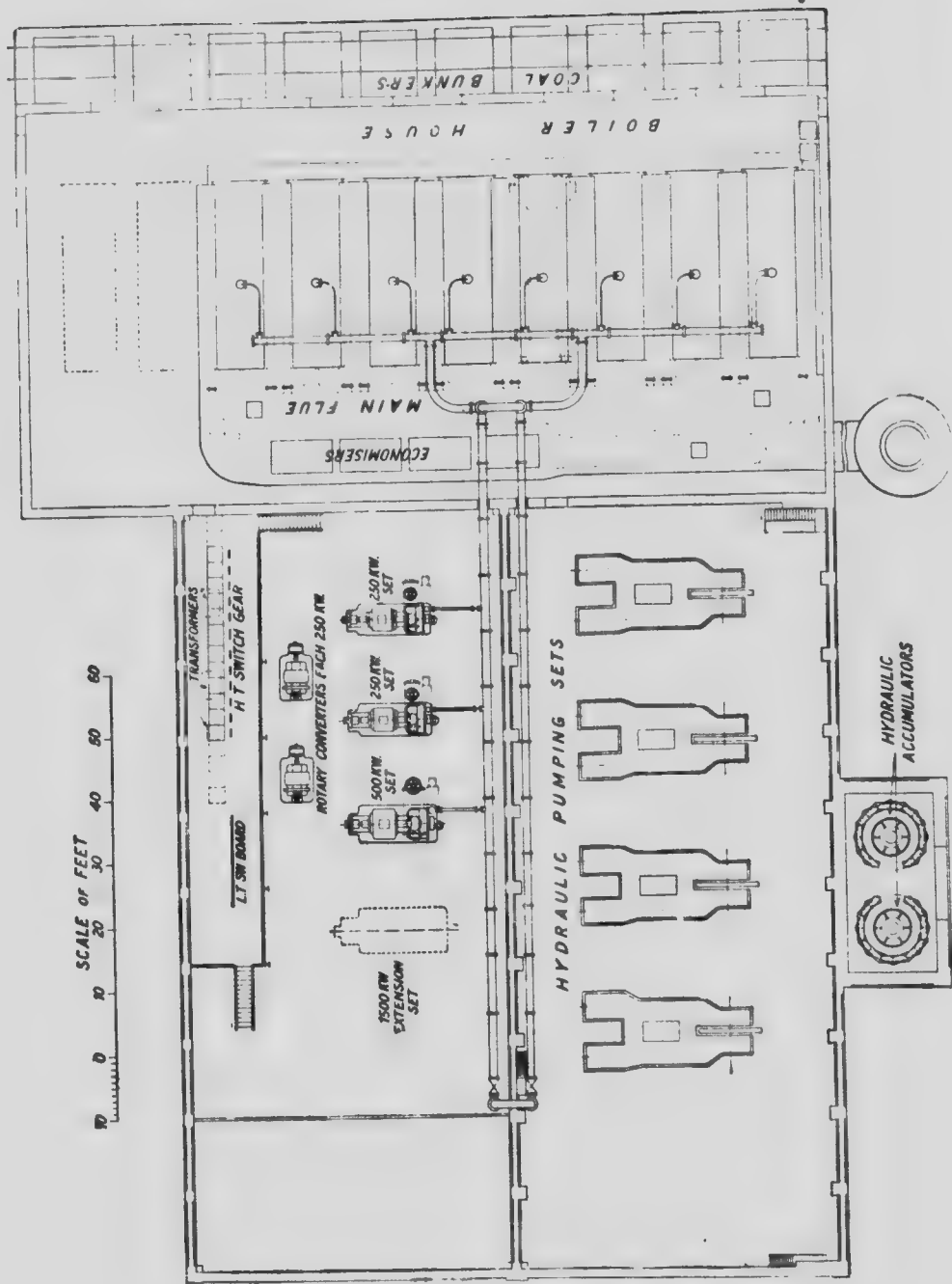
A little further subdivision as regards the fuel section, however, will be useful, as there are different kinds of fuel, and the energy of fuel may be utilised in different ways. The following may be adopted as a working classification:—

Fuel.	Intermediary.	Prime Mover.
1. Coal	Steam	(a) Reciprocating steam engines (b) Steam turbines
2. Coal	Manufactured gas	Gas engines
3. Coal	Waste gas from blast furnaces, coke ovens, etc.	Gas engines
4. Mineral oil	Steam	(a) Reciprocating steam engines (b) Steam turbines
5. Mineral oil	None	Oil engines
6. Spirit	None	Spirit engines
7. Natural gas	None	Gas engines

The above include all the fuels of any importance, the two last being of minor importance compared with the others. By spirit (No. 6) is meant the crude alcohol obtained from vegetable products; this, however, may become of importance as our stores of coal and mineral oil are used up. The last item, natural gas, is not widely distributed, and wherever found hitherto has been quickly exhausted.

II.—ANCILLARY AND SPECIAL ELECTRIC SUPPLY STATIONS

Adopting now the division discussed on page 370, we propose to describe in this section a few typical stations in which either the generation of electric power is ancillary to the chief purpose of the industrial undertaking, or in which such generation is designed for a particular purpose.



Immingham Docks.—A good modern example of an electric generating station ancillary to the chief business of the undertaking is afforded by

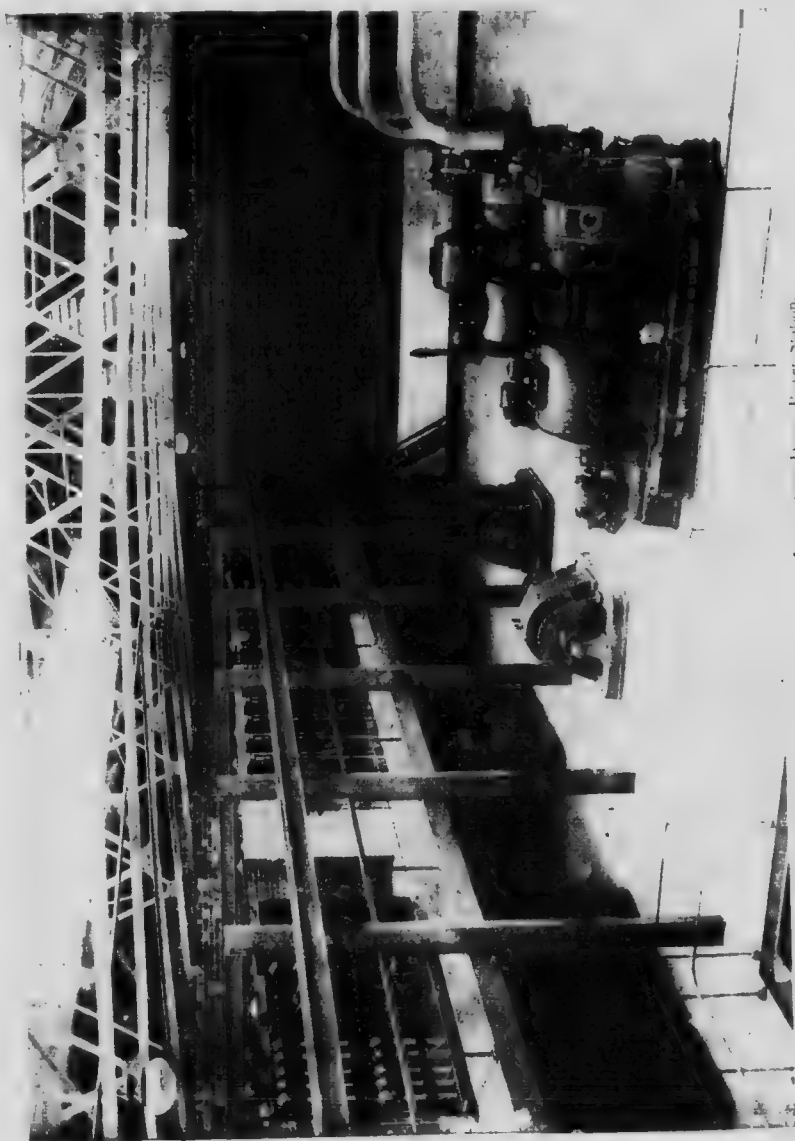


Fig. 357.—Electric Generator Room, Immingham Docks Power Station.

the power station attached to the Immingham Dock recently constructed by the Great Central Railway Company. The ground plan of the station

is given in Fig. 388, and a view of the engine room showing three alternator sets, two rotary converters, and the switchboard gallery, etc., is given in Fig. 389. The dock is about seven miles from Grimsby, and has been constructed to supplement the accommodation there. It is designed to deal with large ocean-going steamers.

It is interesting to note that the power house is partly electric and partly hydraulic, showing that in the opinion of the projectors the latter form of transmission is for certain of the purposes in view regarded as more convenient than the former. Both sets of plant are supplied with steam by a ring main served by the same battery of boilers, which is placed across the ends of the two engine rooms, a position which, as is shown else-

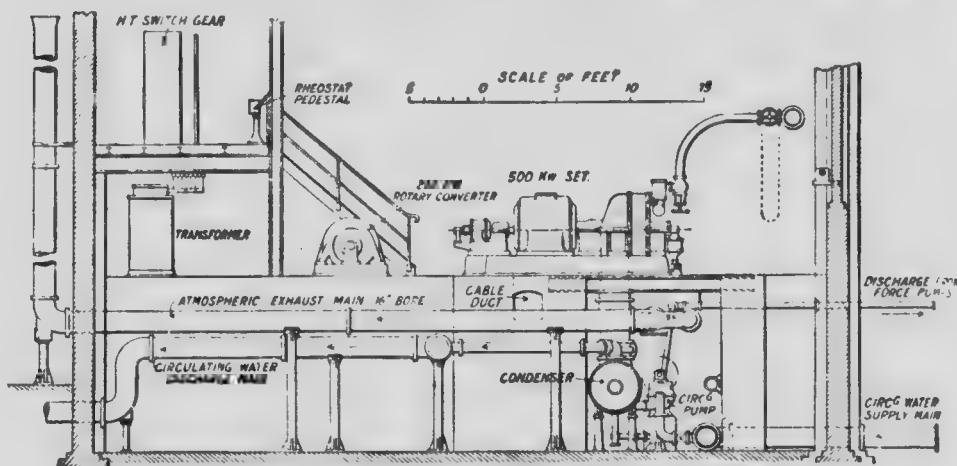


Fig. 390.—Sectional Elevation of Immingham Docks Generating Station.

where, is not an ideal one for large stations. Incidentally, the adjacent engine rooms supply an object-lesson in the relative amount of space required for the two types of generating plant. The four hydraulic sets are rated at 630 H. P. each, or a total of 2,520 H. P. The four electric sets, three installed and one being erected, aggregate 2,500 kilowatts or 3,330 H. P., and occupy far less floor space.

The turbo-alternators consist of horizontal Curtis turbines, driving British Thomson-Houston alternators, the complete sets being built by the British Thomson-Houston Company, some of whose generators have already been described (*see* page 290). As will be seen from Fig. 389, the complete installation will consist of two 250-kilowatt, one 500-kilowatt, and one 1,500-kilowatt sets. A cross-sectional elevation, showing the 500-kilowatt set and its accessories is given in Fig. 390. This should be carefully studied, as it exhibits many interesting and essential details common to much larger stations to be described later.

The electric energy is generated at 6,600 volts and 50 Ω , but is all converted into continuous current energy at suitable voltages before being used for lighting and traction. In this respect the installation resembles a public supply station, inasmuch as five sub-stations are supplied with high-voltage alternating current, which they transform into low-voltage continuous current for distribution to the utilisation plant. The nearest of these sub-stations is in the engine room of the generating station itself, in the form of the necessary transformers, the two rotary converters, and the low-pressure switchboard. The other four are in various convenient positions for the work required, the farthest away being at



Fig. 391.—Gas-Driven Power Station in Shipbuilding Yard.

the Grimsby docks, where it supplies lighting and power through a three-wire distributing network with 460 volts across the outers. The details of such transmission and sub-station transformation will be dealt with later.

Cammell, Laird & Co.'s Shipbuilding Yard.—The next example chosen is the generating station depicted in Fig. 391, which is the power station of the Tranmere Works of the well-known shipbuilding firm of Cammell, Laird and Co., and it well illustrates the variety of the power requirements of a modern shipbuilding yard. It contains no fewer than ten power-driven sets, six of which are electric, two pneumatic, and two hydraulic, the aggregate rated power of the different driving engines in the three cases being 1,950 H. P., 520 H. P., and 160 H. P. respectively. The pneumatic sets, that is the air compressors, are required to opera...

the numerous pneumatic tools used in shipbuilding, and incidentally they furnish compressed air for the starting of the larger gas engines.

The station is driven entirely by gas engines supplied with gas made in the works. A view, on a small scale, of the gas-making plant is given in Fig. 392. The fuel to be gasified is fed into the cast-iron charging hoppers from the elevated charging gallery, which can be readily made out; it then passes through charging bells into the producers, whence the gas, after passing through a mechanical washer, two centrifugal cleaners, and a sawdust scrubber, is delivered clean and cool, ready for use in the gas engines of the power station. The process will be referred to more fully later.

The electrical energy supplied to the works is in the form of both con-



Fig. 392.—Gas Making Plant at Cammell, Laird and Co.'s Yard.

tinuous and alternating current, the former being used for lighting and variable-speed motors, and the latter for constant-speed motors. Electric power is also supplied to the Birkenhead Iron Works of the same firm, which are about half a mile distant, the transmission lines being aluminium cables carried on telegraph poles.

Coltness Ironworks.—In the severe competition of modern industry the utilisation of waste products plays an important part. A striking example is furnished in ironworks where the waste products of the blast furnaces and coke ovens are no longer neglected, but are utilised in various ways. For our purpose the use of the blast-furnace gases for the production of power is perhaps the most interesting, as the power so obtained can very frequently be most conveniently distributed for the various subsidiary power requirements of the works themselves as electric power. An example—supplied by the Coltness Iron Company's works at Newmains, in Lanarkshire—is given in Fig. 393, which depicts a gas engine of 1,250 B. H. P., which is supplied with gas from the blast furnaces after it has been passed through a by-product recovery plant and has been afterwards cleaned. The gas engine is of the Cockerill-Westgarth tandem type, and drives the slow-speed Scott and Mountain alternator shown. This alternator is rated for an output of 850 kilowatts at 100 R. P. M. on a power factor of 0.85. It therefore gives 1,000 kilovolt-amperes, and as its revolving field magnet has 30 poles the periodicity is 25 ω ; the current generated is

three-phase, the pressure being 2,500 volts per phase. This large amount of power is entirely absorbed by the various machines, etc., in a cement mill which deals with one of the other waste products, the slag of the blast furnace, and manufactures from it 1,000 tons per week of cement equal to the best Portland cement. The whole series of complicated operations in which electricity plays an important and, practically, an indispensable part is a most interesting example of modern methods of utilising waste products.

In the same works there is an interesting example of the utilisation

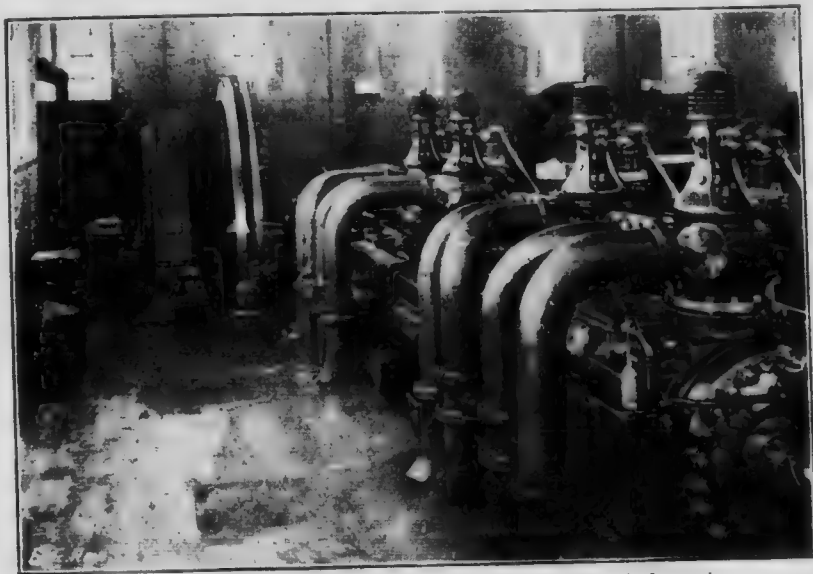


Fig. 393.—Generating Plant driven by Blast-Furnace Waste Gases in Ironworks.

of exhaust steam for the production of electric power. Fig. 394 shows a low-pressure Rateau turbine, which takes the exhaust steam from two blowing engines and drives a 500-kilowatt Brown, Boveri continuous current dynamo, the power from which is used for lighting the works and for driving various auxiliary motors. By means of a 500-kilowatt Scott and Mountain motor generator, this plant and the gas-engine plant can be coupled together, thus adding considerably to the practical flexibility of the whole installation.

Plants for Exceptional Cases.—A class of cases in which it may be deemed necessary to install costly generating plant, notwithstanding the fact that public supply mains are accessible from which power can be obtained at a reasonable rate, is that of those polytechnics and technical institutes in which the training of electrical engineers is a prominent

part of the work. Such schools, especially in London and the larger towns, are attended by students who are daily handling, or will shortly be handling, the most modern and up-to-date apparatus and machinery, embodying the latest results of scientific and engineering investigations. It is useless in the advanced classes to attempt to give practical teaching to such men with makeshift apparatus, though for the fundamental experiments of elementary classes such apparatus may be more educational than the most highly finished products of the machine shop or the instrument shop. For the advanced students who are already engineers, or nearly so,

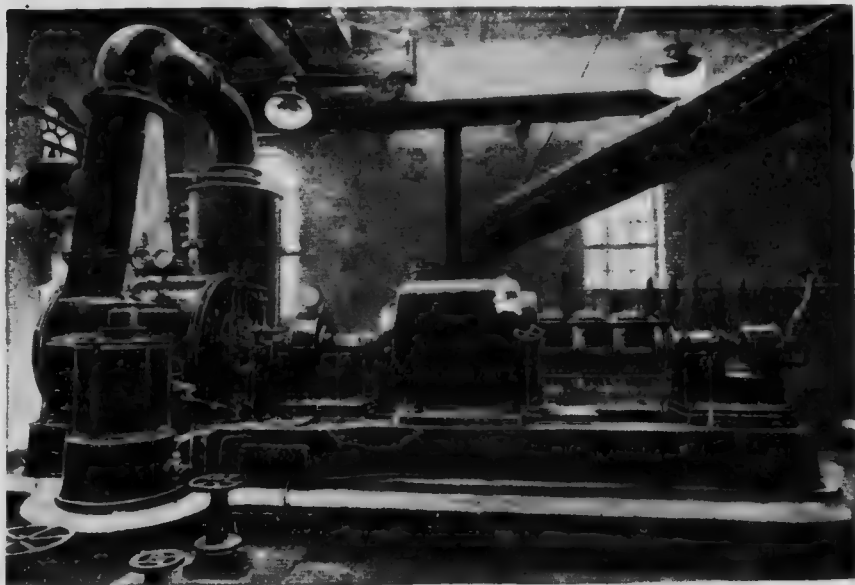


Fig. 394.—Low-Pressure Turbines Driven by Exhaust Steam from Blowing Engines in Ironworks.

the real thing must be provided, and on a sufficiently large scale to make the experiments engineering experiments, and not toy experiments.

As the institutions of this grade usually require a fair amount of energy for lighting and power purposes, it is but reasonable that these should be supplied from a generating station on the premises in which the students can study on an engineering scale some of the problems of a large public supply station, and if the equipment of the station be carefully designed much work of high educational value can be done in it.

Northampton Polytechnic Institute, London.—As an example with which the author is necessarily very familiar, some description of such a station at the Northampton Polytechnic Institute may usefully be given here. The contractors for the whole station were the well-

known firm of Siemens Brothers, who worked to specifications drawn by the technical staff of the Polytechnic. The generating plant consists of two 100 H.P. six-cylinder Gardner gas engines, supplied by Messrs. Norris and Henty, and each driving a 50-kilowatt continuous current dynamo and a 50-kilowatt alternator coupled together on the same shaft. One of the engines, with its two generators in the background, is shown in Fig. 395, whilst the two lines of machines as they appear from the generator end are depicted in Fig. 396. The engines are supplied with

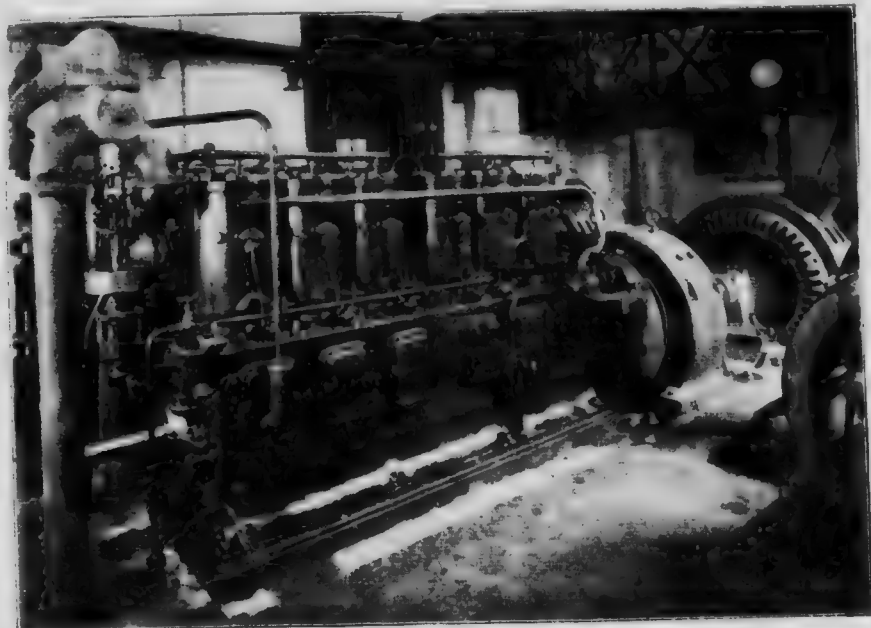


Fig. 395.—High Speed Gas Engines, Northampton Polytechnic Institute, London.

gas from a producer plant erected by the Campbell Gas Engine Company, with an ample margin of total power, and well adapted for experimental purposes. As a stand-by and for times when it would not be economical to start up the producer plant, connections to the public gas mains are provided. The cooling water for the water-jacketed cylinders is obtained from the adjacent large swimming bath of the Polytechnic, which forms a very efficient cooling pond. For lubrication, most of the working parts are enclosed in the crank case, which contains an oil bath, and forced lubrication is provided for the main and connecting-rod bearings. The normal speed is 500 R.P.M., and as there are six cylinders running on the well-known Otto cycle with one explosion in every two revolutions, it follows that there are twenty-five explosions per second, which must be

accurately timed to follow one another in regular sequence. The sparking gear has therefore to be both well designed and well made to be reliable.

The continuous current Siemens generators, which are placed nearest to the engines, have, as already stated, an output of 50 kilowatts each, the standard voltage being 220 volts; but this may be varied between 200 and 230 volts by hand regulation of resistance in the shunt circuit. The field magnets are compound wound, being over-compounded so as to give a rising P. D. at full load.

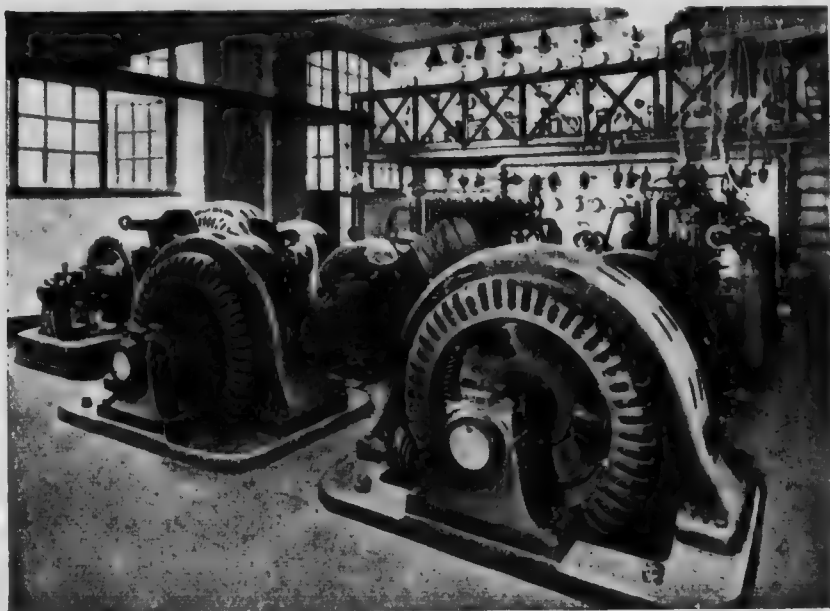


Fig. 396.—A. C. and C. C. Generators, Northampton Polytechnic Institute, London.

The Siemens alternators, which are in tandem with the continuous current machines, are driven through a coupling which can be thrown out of action when desired, though this is seldom done. They are of the revolving-field type, and their field magnets have six poles with laminated pole faces, the current generated therefore having a periodicity of 25 ω . The fact that the periodicity necessarily corresponds to the number of explosions per second in the engines has led to some interesting problems in paralleling. The armature, the housing of which can be seen in Fig. 396, is of the open-slot type, well ventilated, and with the coils held in their places by wooden keys. It is wound for three-phase currents, and as the six ends of the windings are brought out, they can be connected up either in star or mesh, the standard voltage in star being 2,200 volts

per phase. The exciting current for the field magnets is supplied from the low-pressure continuous current switchboard at the normal pressure of 220 volts through two gun-metal slip-rings shrunk on the shaft, from which they are insulated by micanite.

The temperature rise of all the generators is guaranteed not to exceed 70° Fahr. after six hours run at full load; they will stand a 25 per cent. overload for one hour and a momentary overload of 50 per cent.

It is interesting to note that the guaranteed over-all efficiencies of the generators are as follows:—

	C.C. Dynamo.		Alternator.	
Full load	88	per cent.	86½	per cent.
Three-quarter load ..	87½	"	85½	"
Half load	85½	"	82½	"

the power factor of the alternating circuit being 0.85. The voltage drop between no-load and full non-inductive load of the alternators is less than 10 per cent. at constant speed and excitation, and the wave form is guaranteed to contain no harmonic with an amplitude exceeding 2 per cent. of the amplitude of the fundamental sine wave, the maximum deviation permitted from a true sine wave being 5 per cent. The actual wave form obtained has been already referred to in detail on pages 343 to 345.

The station also contains a secondary battery, a motor generator set, transformers, a rotary converter, and very complete switchboards of modern type, most of which will be referred to later in the proper places.

Royal Mint.—An interesting generating station of the kind with which we are dealing in this section, and one which will probably appeal to the imagination of the reader, is the new generating station of the Royal Mint. The Mint is so placed that it could probably obtain the necessary energy for the requisite power and lighting purposes from public mains, but this is perhaps a case in which it would be readily conceded that the building and equipment should be so planned that the necessary operations should all be contained within the four walls, and not be dependent from hour to hour on outside assistance. However that may be, the Royal Mint has always had its own power stations, the most recent and modern of which is shown in Fig. 397. It is a steam-driven station, the boiler plant being available from the older-fashioned period, when marine-type steam engines and complicated shafting were employed. There are two generating sets, each consisting of a Willans high-speed vertical reciprocating engine direct-coupled to a Siemens continuous current dynamo having an output of 200 kilowatts at 110 volts. The buildings are very compact, and no point where current is required is very distant from the power station; hence, the advantages of low-voltage working can be secured without much sacrifice in economy. The switchboard, which can be seen on the other

side of the dynamos, is of the simple plug type, which will be described later. By it any distributing circuit can be put either on the modern station or on an older station in which there are four 80 H. P. sets giving continuous current at the same voltage. The total horse power available is therefore 850, of which the various motors can absorb from 600 to 700. For night load there are two E. P. S. secondary batteries, which can give a steady discharge of about 80 kilowatts, which is ample for all purposes when the machinery is not running.

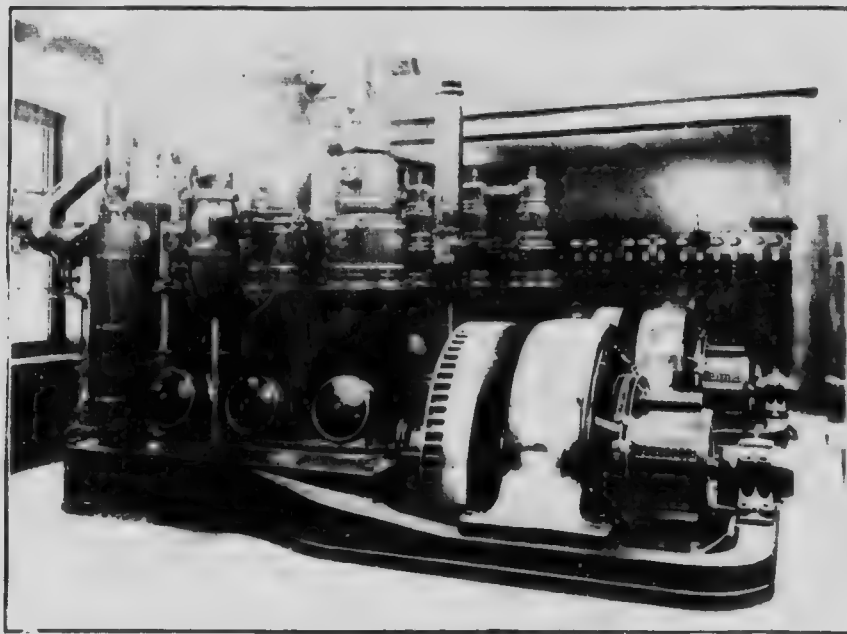


Fig. 197.—Generating Station at the Royal Mint, London.

General Post Office, London.—A generating station which more nearly approximates to the large public supply stations to be described later, but which, as it is really incidental to a very different series of undertakings, more naturally falls into the present section, is the new power station of the General Post Office which was started to supply power to the group of post office buildings in the neighbourhood of St. Martin's le Grand in November, 1910.

The power handled—some 2,500 kilowatts—is quite considerable, and it can readily be imagined that it would have been extravagant to provide space for the generation of this amount of power within the expensive area of the City of London when much cheaper space was available within

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Fig 398.—Generating Station of the General Post Office - London.

a comparatively short distance on the other side of the river at Blackfriars. A suitable site having been found in the cheaper locality, the station has been erected there.

An interior view of the engine room of the station is given in Fig. 398. The generating plant consists of two Dick, Kerr turbo-alternators of the open type, similar to those already described, each having an output of 1,000 kilowatts at 1,500 R. P. M., and a turbo-alternator of the closed stator type having an output of 500 kilowatts at 3,000 R. P. M. Each alternator is driven by a Willans-Parsons turbine, the current generated being three-phase at 6,600 volts per phase and 50 periods per second. The smaller

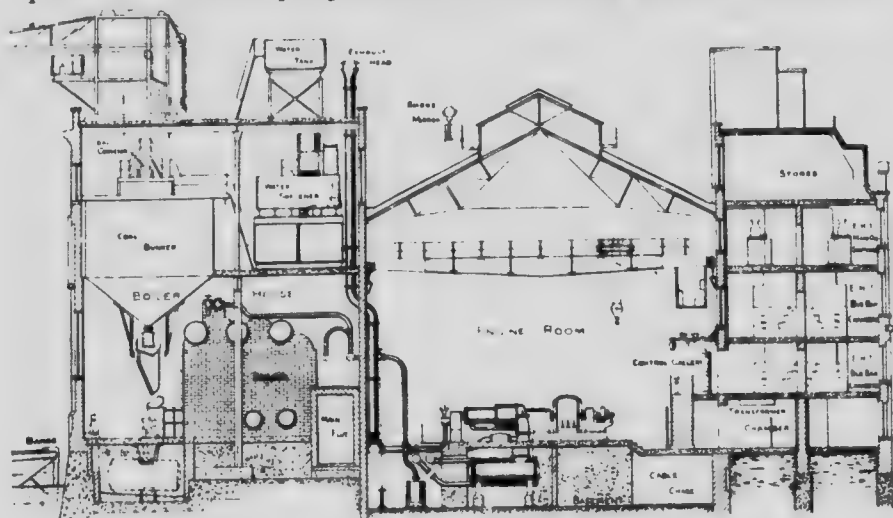


Fig. 399.—Sectional Elevation of the G.P.O. Generating Station.

set is bipolar, whilst the larger sets have four-pole rotors. The exciter for each alternator is driven through a flexible coupling by the same turbine shaft, and is carried on an extension of the end pedestal, a method to which reference has previously been made (*see* Figs. 220 and 345). If necessary, the fields can be excited from the auxiliary plant. Each set is capable of carrying a 50 per cent. overload for two hours, and therefore, if sufficient steam could be supplied, the station could for that length of time deliver power at the rate of 3,750 kilowatts.

The auxiliary plant seen on the left of the picture (Fig. 398) consists of a dynamo and a motor generator set, each having a capacity of 35 kilowatts. The dynamo is driven by a Willans and Robinson reciprocating vertical high-speed engine, and delivers continuous current at 110 volts to the low-pressure switchboard. The motor generator set can be worked either from the continuous or the alternating current side; it can take energy from the

low-pressure continuous current busbars or from either the low- or high-pressure alternating current busbars. In the last-named case an induction motor drives the continuous current generator of the set.

A sectional elevation and a plan of the station are given in Figs. 399 and 400, and are worth careful study. The station being on the banks

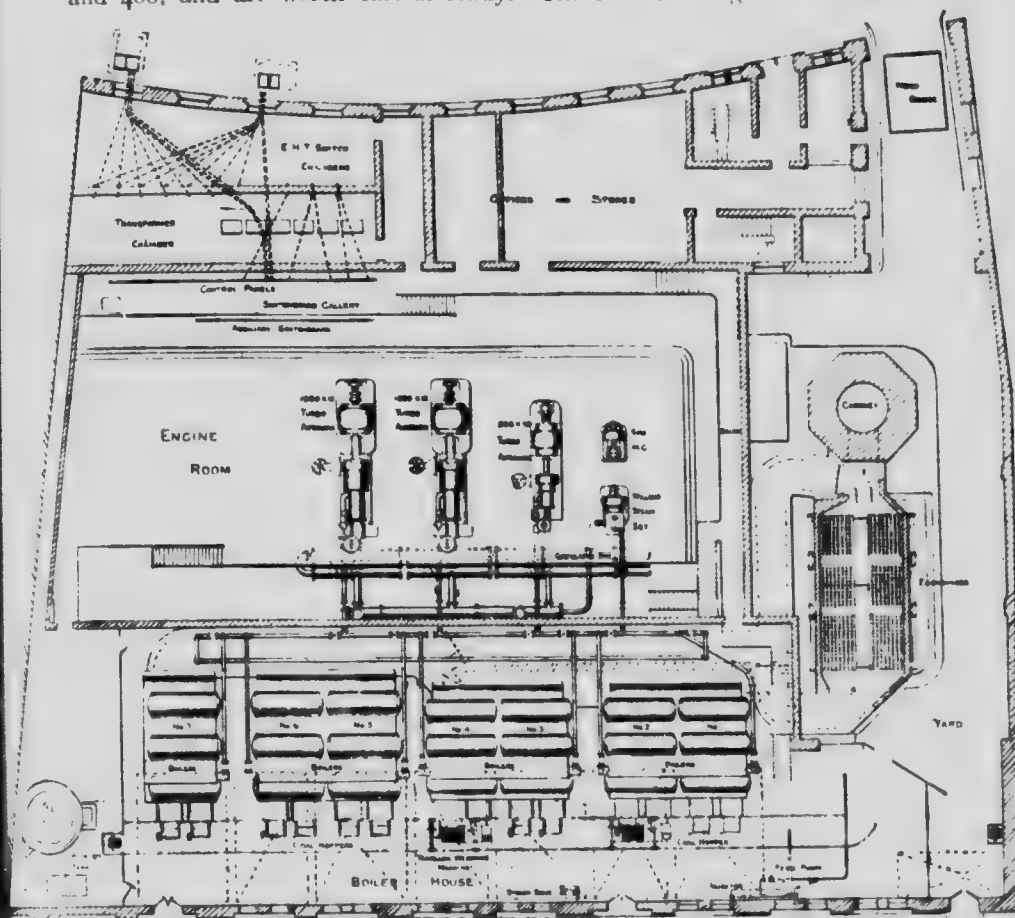


Fig. 400.—Plan of the G.P.O. Generating Station.

of the Thames, the coal is delivered to it in barges, whence it is hoisted by a roof crane and, after being weighed, is conveyed to the bunkers by the usual appliances. The boiler room is parallel to the engine room, the economiser and chimney being at the end of the engine room. There is a battery of seven Stirling water-tube boilers having a total steam-raising capacity of over 130,000 lb. of steam per hour when they are all

under full steam. The disproportion between the space, whether floor space or cubical space, occupied by the steam-raising and the steam-using plant is very marked; it is a feature of all large stations in which turbo-generators are installed, and one to which we shall draw more detailed attention later.

The switching and transmission arrangements, and the somewhat unique utilisation of some of the power generated at this station will be dealt with in subsequent pages.

III.—BATTERIES OF GENERATORS

From the foregoing it will be obvious that in many cases in practice it is necessary from time to time to increase the generator output in an electric supply system for a longer or shorter period. If the machine or machines already at work are fully loaded, this can only be done by bringing into action additional machines, and in doing this certain problems arise, partly dependent on the type of machine in use and partly on the system into which it is to be introduced and to the part it has to play in that system. These problems depend so much for their solution on the principles which underlie the design and construction of the generators, that it will be convenient to deal with them here before we proceed to the consideration of large modern supply stations in which the solutions of such problems are continually being required.

The problems to be solved, so far as they depend on the generators, divide naturally into two classes, according as the machines to be dealt with are continuous or alternate current dynamos. In regard to the system of supply, the incoming machine may be required to increase the output by increasing the current without changing the pressure, or it may be required to increase the output by increasing the pressure without change of current. The third possible case, where both current and pressure are to be considerably changed by the incoming machine, does not occur in modern practice. The generators, when working together, may be conveniently described as "batteries," as they are electrically analogous to combinations of voltaic cells. The two chief divisions into which such batteries fall are (i.) continuous current batteries and (ii.) alternate current batteries.

III. (i.)—CONTINUOUS CURRENT BATTERIES

To form these it may be desired to join the generators in series or in parallel; with the large and varied outputs of modern generators a series-parallel combination is seldom required. The method to be followed in bringing in additional continuous current machines—which, it must be remembered, are self-exciting generators—will depend upon the mode of excitation, or, in other words, upon whether the machines are (i.) series-, (ii.) shunt-, or (iii.) compound-wound dynamos.

Generators in Series.—As this is the simpler, though not at present the most usual, case, it will be considered first. The machines available should be regulated for constant current (see pages 192 to 197), and to form part of the same battery this current must be the same for each machine.

Series Dynamos.—This is the simplest case of all, as the machine (Fig 483, Vol. I.) has but one circuit through its armature and field coils in series. Having run the machine up to its normal speed, an obvious precaution to take is that the current from the other machines is passed through in the direction necessary to ensure that the polarity will be right when the new machine becomes fully excited, so that $+$ terminal will be joined to $-$ terminal all along the line. The machine will be switched into the supply circuit and removed from it exactly in the same way as

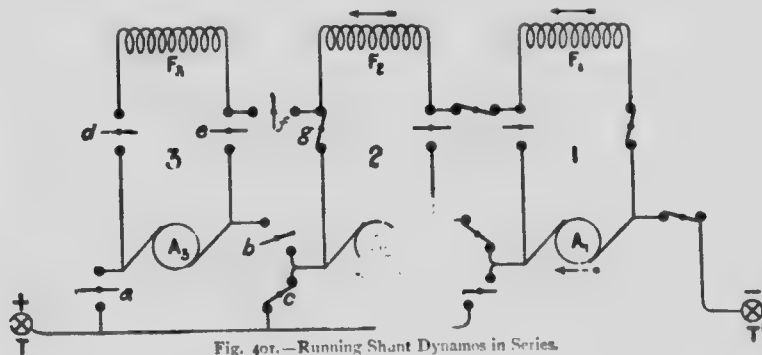


Fig. 401.—Running Shunt Dynamos in Series.

any other piece of constant current apparatus. When it is fully excited, it will be necessary to adjust its speed so that it takes its fair share of the whole load, as indicated by a voltmeter placed across its terminals.

Shunt Dynamos.—When shunt dynamos are run in series their exciting circuits—except at the two terminals—should be disconnected from the brushes and placed in series across the extreme terminals. This will ensure that each exciting coil has the same current, for it is assumed that the machines are similar—a condition which will usually obtain in practice. The method of bringing in the new machine can be followed by reference to Fig. 401, which represents two dynamos 1 and 2, with their armatures A_1 and A_2 and field coils F_1 and F_2 in series on the terminals T and T' , and a third dynamo 3, not yet in circuit, and with its field magnets not excited. Dynamo 3 having been run up to its normal speed, switches a and b should be closed and switch c opened. This will run the constant current from the other dynamos through A_3 as a practically dead resistance. Now close switches d and e so that the field coil F_3 of dynamo 3 will receive

current, and the magnetism will "build" up until the P. D. across the brushes is equal to the P. D. of each of the other machines, which will probably be less than it was before, as their exciting currents may be temporarily diminished. The switch *f* can now be closed and the switches *e* and *g* opened, leaving the three armatures A_1 , A_2 , and A_3 in series across the terminals T and T' , and the three field coils F_1 , F_2 , and F_3 in series across the same terminals.

To remove dynamo **3** from the circuit when it is no longer required switches *e* and *g* should first be closed and switch *f* opened. The dynamo can now be slowed down, and when its magnetism has disappeared, switch *c* can be closed and switches *a* and *b* opened, thus disconnecting it from the circuit.

If the machines are not similar their fields cannot be placed in a series

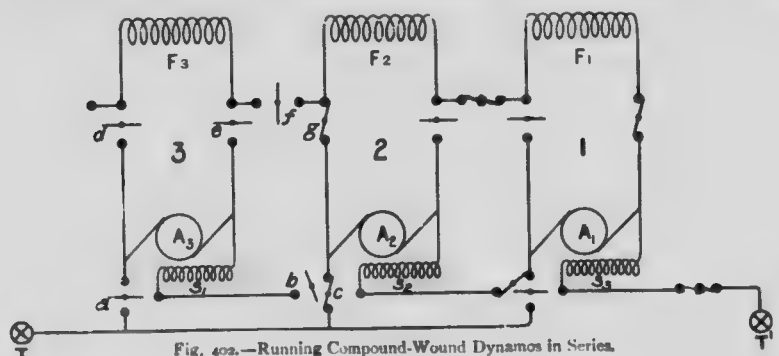


Fig. 402.—Running Compound-Wound Dynamos in Series.

circuit separate from the armature circuit. In this case it will be found more difficult, though not impossible, to adjust a varying load fairly between the different machines in series.

Compound-Wound Dynamos.—This case is to be dealt with precisely as the last, the series coil being treated for a long-shunt (Fig. 2) as part of the armature and for a short-shunt (Fig. 1) as part of the connecting lead between the armature and the terminal of the machine, the one additional precaution, perhaps, being that after closing the switches *a* and *b*, the switch *c* should be at once opened, though as a rule the current through the series coils alone will not be sufficient to excite the field of the dynamo. A diagram of the connections is given in Fig. 402, in which the series coils S_1 , S_2 , and S_3 are shown for short-shunt compounding, and the same reference letters are used as in Fig. 401. The switches are to be manipulated in the order described above.

The principles underlying the use of dynamos in series have been rendered important through the successful experiments of M. Thury and others on the employment of high-voltage dynamos in series for high-

voltage transmission of energy by means of continuous currents. The ultimate pressure reached has exceeded 50,000 volts. It is necessary to point out that wherever the pressure is even much lower than this the machines and all circuits, switches, and apparatus connected therewith must be very carefully insulated, and operated with proper precautions to ensure safety. Suitable high-voltage switches, etc., will be described later.

Generators in Parallel.—As the more usual method of supplying electric energy is to keep the pressure on the mains constant, and to increase or diminish the supply by increasing or diminishing the current, it is frequently necessary at times of heavy load to add additional generators in parallel to the battery to furnish the additional current required. As the load diminishes these additional machines can be cut out of circuit, the aim of the engineer being to keep each unit of plant which is running as nearly fully loaded as is possible. The methods of switching in and out depend, as in the cases considered above, on the method of excitation of the dynamos.

Series Dynamos.—This case is not usual, but as it may occur it will be well to deal with it. The points to be borne in mind are that a series dynamo, even though running at full speed, is "dead" until current is passed through its field coils, and that therefore such a dynamo should not be placed on "live" busbars without precautions being taken to prevent a rush of current, which would reverse the magnetism of its field magnets, with disastrous consequences.

Arrangements must therefore be made to excite the fields before the armature circuit is closed, and this can be done by the method shown in Fig. 403, in which two series machines 1 and 2 are shown as already running in parallel on the busbars A and B. The third machine 3 is supposed to be running at full speed, but with all switches open, and therefore "dead." The switches *a* and *b* are to be closed first, thus passing current through the field coil F_3 from the other machines, and causing the magnetism of 3 to "build"; as soon as the voltmeter across the brushes of the armature A_3 shows that the requisite E. M. F. has been developed the switches *c* and *d* can be closed.

The cross switch *a* must be left closed during the running of the machine so as to ensure that the field current shall always pass through F_3 in the right direction. If this switch were open, should the E. M. F. of A_3 from any cause drop, there would be a danger of the current through the machine

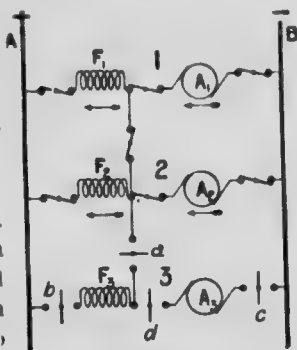


Fig. 403.—Running Series Dynamos in Parallel.

being rapidly reversed. For the first effect of the drop of the E. M. F. would be that the machine would not contribute its proper proportion of current to the busbars; its field would therefore be weakened, and the E. M. F. would drop still lower, with further weakening of the field, until very rapidly the P. D. of A and B would be greater than the E. M. F., and the current would then reverse, reversing the field; and the E. M. F., and causing an enormous current to pass from A to B through the machine. Now, although with *a* closed it is still possible for the current in the armature A₁ to be reversed if its E. M. F. should fall too low, yet the current in F₁ will be maintained in the right direction, and therefore there will always be an E. M. F. in the right direction in A₃, for 3 would then be a separately excited machine. Long before mischief could develop either an automatic switch should open or the switchboard attendant should have found out that something was wrong, and have taken steps accordingly.

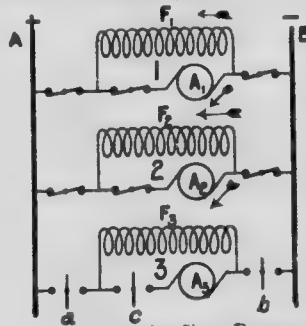


Fig. 404.—Running Shunt Dynamos in Parallel.

In removing the machine from the circuit its speed should be reduced slowly until there is practically no current in the armature, when the switches *c* and *d* can be safely opened, leaving the field magnets excited. Before opening either of the switches *a* or *b* a discharging resistance should be placed across the terminals of F₃ to absorb the energy of the magnetic field when the switches are opened.

It will be gathered from the above that the regulation of series dynamos running in parallel requires constant supervision, and may be troublesome; hence the preference given in modern practice to shunt and compound-wound machines.

Shunt Dynamos.—Similar precautions must be adopted for an incoming machine, as in the last case, namely, (i.) to run it up to full normal speed, and (ii.) to excite its field magnets before closing the armature circuit. The necessary arrangements are shown diagrammatically in Fig. 404, and are very simple. As before, two dynamos 1 and 2 are already on the busbars A and B, and a third machine 3 is running and ready to be switched on. On closing the switches *a* and *b*, the field coils F₃ receive a full exciting current from the busbars, and as soon as the E. M. F. of A₃ reaches a little over the busbar value, the switch *c* may be closed, and the speed, or excitation, of 3 adjusted until it takes its proper share of the load.

To take out of circuit, the speed should be gradually diminished until the machine is giving little or no current to the busbars, and then the switches *a* and *b* can be opened safely and the machine allowed to slow down to a standstill before opening the switch *c*.

It will be noticed that there is no danger of the magnetism reversing, even though the E. M. F. should fall so low that the current through the armature is reversed. If this should happen, the machine would be driven as a motor from the busbars, but before this state of things could be set up an automatic switch at *c* would usually open the armature circuit.

Compound Dynamos.—With compound-wound machines the method to be followed is a little more complicated, either when, through increase of load, another dynamo is required, or on taking out a dynamo as the load diminishes. The proper method was first pointed out by Mr. Mordey, and is shown diagrammatically in Fig. 405. $T_1 T_1$ and $T_2 T_2$ are the busbar connections of two compound-wound dynamos supplying constant potential mains; A_1 and A_2 represent the armatures, and the thick- and fine-line spirals are intended to represent respectively the series and shunt circuits of the field magnets. Each dynamo has a switch in its shunt circuit, and another in its armature circuit between the brush and the junction with the shunt circuit. The brushes $B_1 B_2$ next to the inner ends of the series coils can also be connected by a separate conductor, in which there is an additional switch *z*.

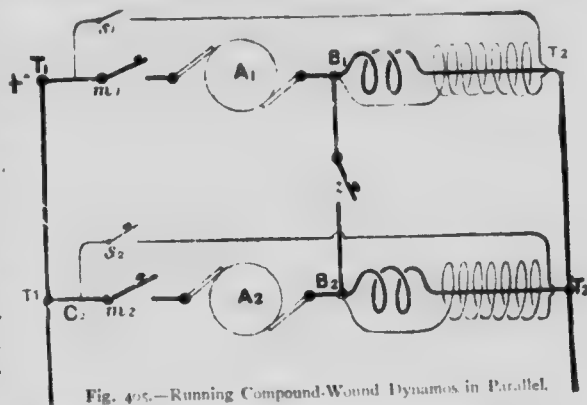


Fig. 405.—Running Compound-Wound Dynamos in Parallel.

Now suppose the machine A_1 to be running, with its switches s_1 and m_1 of course closed, and it is required to bring into circuit the machine A_2 , the following is the method of procedure:—First run the armature A_2 up to full speed and close the switches s_2 and *z*. This will cause the field magnets to be excited to full strength by both series and shunt coils, the requisite currents being supplied by A_1 . As soon as the full magnetisation is developed, the armature A_2 will be found to be generating the requisite E. M. F. and then the switch m_2 may be closed and the operation is complete.

By thus connecting both ends of all the series coils in parallel it becomes impossible to reverse the current in any of them, a contingency that might easily occur if the conductor $B_1 B_2$ and its switch were omitted. The evil of such a reversal is evident, as the series coil would then become a *demagnetising* coil, weakening the field magnets, and therefore lowering the E. M. F. and tending to cause a reversal of current in the armature, as in the cases already referred to.

In taking out this second machine the difficulties above described must

be borne in mind. The machine having been slowed down until it is supplying no current to the busbars, a switch at c_2 (not shown in the figure, and which might be automatic) should be opened, disconnecting the machine from the $+$ busbar. The coupling switch z can next be opened, removing the current from the series coils; this can be done safely, for the field set up by this current, which is the regulating current, will not be very great. The machine can then be stopped, and the switches m_2 and s_2 opened.

A more detailed diagram of the connections for joining two compound dynamos in parallel is given in Fig. 406,* issued by the Crocker-Wheeler Company as instructions to dynamo users. The separate conductor containing the switch z (Fig. 405) is represented by an "equaliser" bar, which is placed below the busbars on the switchboard, or in some other more convenient position. The diagram (Fig. 406) represents two compound machines with short-shunt winding, No. 1 being an eight-pole and No. 2 a six-pole machine. The eight-pole machine is running, and is connected to the busbars and the equaliser by the triple switch s^1 . To bring on No. 2 it is first to be run up to full speed and its shunt-field circuit closed by the multiple contact switch F^2 , which is to be adjusted until the voltage across the brushes is one per cent. higher than the busbar P. D. The triple switch s^2 is then to be closed, and the switch F^2 further adjusted until No. 2 machine takes its proper share of the load. The reader should carefully trace out the connections in Fig. 406 and compare them with the simpler diagram of Fig. 405, when they will be found to be similar, both shunt circuits being connected to the brushes for a short-shunt winding; also that in Fig. 406 the regulating switches F and the equaliser bar and its connections have been added.

The "equaliser bar" or its equivalent, shown in Fig. 406, has long since become a permanent feature of the switching arrangements for paralleling continuous current dynamos, for in most cases in which such paralleling is required the machines are compound wound. With, however, the diversity of plant which may sometimes be found in modern generating stations a little care is required if machines of different types and sizes are paralleled on the same busbars with a single equaliser bar for the whole. When the machines are running with the triple switches shown in Fig. 406 closed for each machine, it is obvious that the same P. D. is being used across the switchboard terminals of each series coils. Two cases may arise (1) where all the machines are of the same capacity, and (2) where they are of different capacities.

In the first and simplest case, if all the machines are of the same pattern, requiring the same series currents for compounding purposes, the resistances of all the series coils will be the same, and each machine will

* Lent by the General Electric Company of London.

automatically receive the requisite correcting current as the load rises and falls, provided the resistance of the lead from the brush to the equaliser

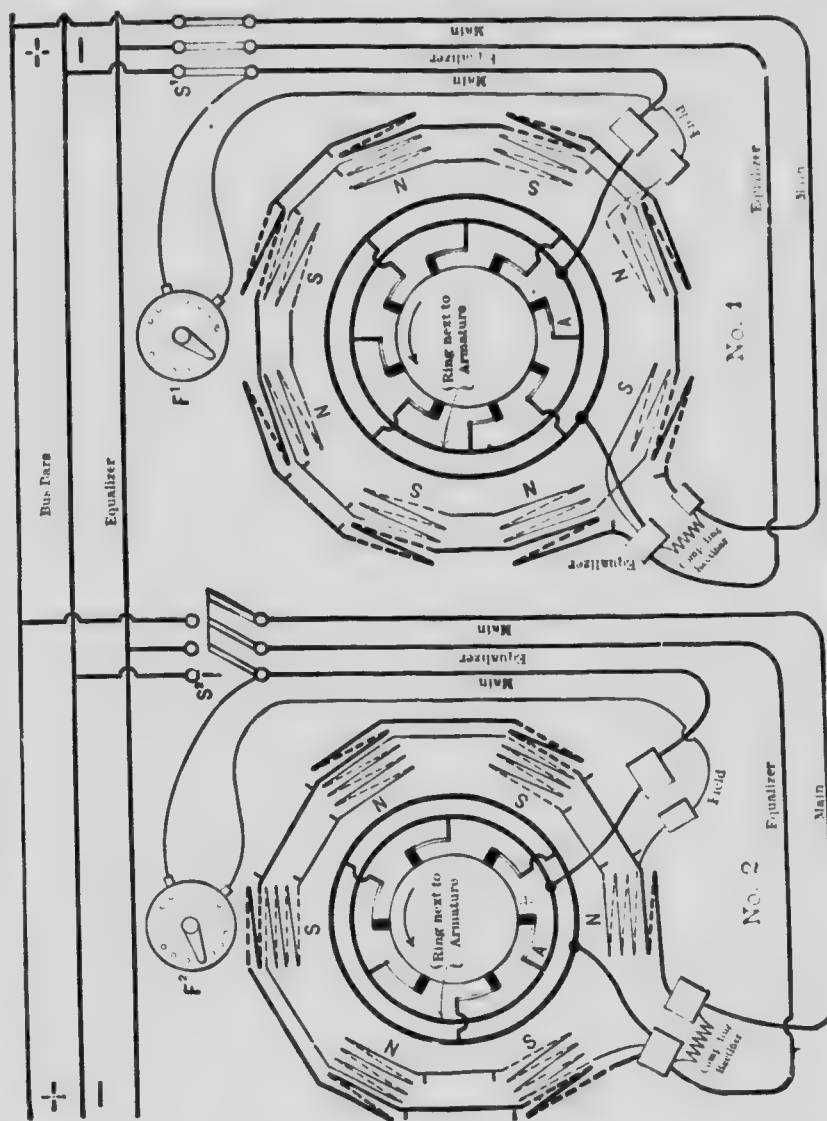


Fig. 466.—Two Co., and Ward, Cuthberts Current System in Parallel

bar is sufficiently low. The matter should not, however, be left to chance but the equality of the resistances, when hot, between busbar brush

terminals should be ascertained, for the resistances of the leads for machines at different distances may seriously upset the required equality, even if the actual magnetising coils have equal resistances.

But even if the machines are of the same capacity, if they happened to be of different types their series coils may not be all of the same resistance without the complication of different lengths of leads. For instance, if some of the machines are slow-speed dynamos and some turbo-dynamos, the series coils of the latter will be of much lower resistance than those of the former, and it will be necessary to introduce into the busbar leads of the turbo-dynamos a resistance to make up the difference, this resistance being, of course, selected of sufficient capacity to carry the full load current.

The "compound rectifier" in the left-hand bottom corner of each diagram in Fig. 406 will be found to be in parallel with the series magnet coils, a device used by the Crocker-Wheeler Company to improve the regulating effect of the series coil. Its action has been fully explained on page 179, when dealing with the regulation of continuous current machines. For details of the various switches, automatic and otherwise, employed in the above operations, the reader is referred to a subsequent chapter.

III. (ii.)—ALTERNATE CURRENT BATTERIES

The question of coupling alternate current dynamos or alternators together is still more complicated. It is at once evident that for two alternators to run together they must either have the same frequency, i.e. the same number of alternations per second, or that the frequency of one must be some very simple multiple of the frequency of the other. Should the numbers expressing the two frequencies be incommensurable, or bear no simple relation to one another, then, on putting the machines into circuit with each other, the two E. M. F.s would reach their successive maxima at different intervals of time, and the resultant E. M. F. produced by adding them together would be subject to violent fluctuations, leading to serious trouble. In practice, the first case cited above—namely, that in which the frequencies are the same—is the only one in which it is attempted to run two or more alternators on the same circuit. Still further, in most cases the machines have not only their frequencies equal, but also are machines of identical build and pattern, though this latter condition is not absolutely essential, and machines of different types have been successfully paralleled in modern stations.

But even supposing the machines to be exactly similar and to be running at equal speeds, so that the frequencies are the same, there may still be a difference between them, for the alternations may not be in the same *phase* (see page 541, Vol. I.). It is obvious that the ordinary distinction of positive and negative terminals, which holds with continuous current

dynamo, does not apply to alternators, since *each* terminal is alternately positive and negative, and changes its polarity every second, just as often again as there are complete alternations. It is therefore evident that if the brushes *A, a* (Fig. 407*) of one machine be joined haphazard to the brushes *B, b* of the other, the circuit *p r p* being supposed to be removed, it may happen that the machines are at the moment either in series or parallel, or in some other intermediate relation to one another. For instance, if at the moment of junction *A* and *b* are simultaneously at their maximum positive potential, and therefore *B* and *a* at their maximum negative potential, the machines are coupled in series with one another, and a full current will flow round the circuit *A B b a*. On the other hand, if *A* and *B* are simultaneously at their maximum positive potential whilst *a* and *b* are at the same instant at their maximum negative potential, the machines are in parallel, and no current can flow round the circuit *A B b a*. Between these two cases all kinds of intermediate phase relations can exist in which the machines are never either strictly in series or strictly in parallel.

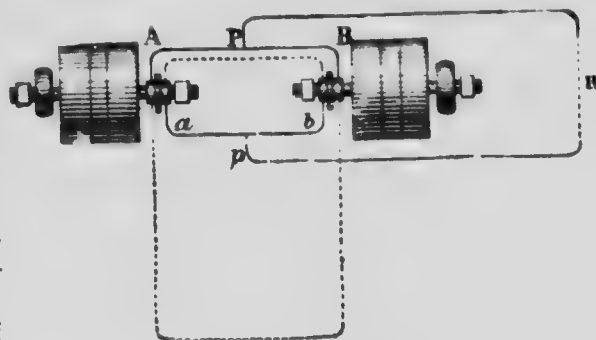


Fig. 407.—Coupling of Alternators.

The problem of coupling the alternators together, therefore,

at first sight looks somewhat too complicated for solution, but fortunately the interactions of the two machines are such as to conduce to mutual regulation. Both mathematically and experimentally it can be shown that if by any accident the machines happen to be placed in series with one another, then, although the condition is one of equilibrium, that equilibrium is unstable. In other words, it is such a state of equilibrium that, if it be disturbed by the slightest cause, the mutual actions and reactions do not tend to restore it, but tend to intensify the disturbance still further. It is similar to the case of an egg balanced on its small end, which, however perfect the balance may be, if it be once disturbed, cannot be restored by the gravitational forces acting on the egg.

The explanation, leaving out the mathematics, is as follows:—Suppose the machines to be running at a particular time in series and in perfect synchronism with one another; sooner or later some slight cause, such as the slip of a belt or something else connected with the working,

* Taken from a paper by Dr. John Hopkinson.

will throw one of them a little behind the other in phase, that is, it will throw them out of step, as it were. When this happens, it can be shown that, although the effective E. M. F. is diminished on account of the phase difference and the current in the circuit $A B b a$ thereby cut down, the lagging machine at once becomes more heavily loaded than the other, and therefore tends to lag still further. Also this heavier loading persists, and therefore the lag (or phase-difference) goes on increasing and the effective E. M. F. and current diminishing through all the intermediate phase relations, until the machines are in directly opposite phases simultaneously, in which case the current sinks to zero and they are really in parallel, as already explained.

This condition is again one of equilibrium, and it can be shown that if, whilst running in parallel, one of the machines, through any accidental cause, lags a little behind the other, then the mutual actions and reactions tend to bring it back into step again. In this case the lagging machine, instead of becoming more heavily loaded than the other, becomes more lightly loaded, and therefore tends to catch up its companion again. Two similar alternators in parallel, and running at the same speed, are therefore in stable equilibrium, and the combination is self-regulating. In this case both ends of the wire $A B$ (Fig. 407) reach their positive maximum simultaneously and at the same time that both ends of $a b$ reach their negative maximum. If now the circuit $P R p$ be added, it will draw currents from both machines, which are electrically in parallel on its terminals $P p$. These self-regulating phenomena of similar alternators were first investigated and pointed out by Dr. John Hopkinson in 1883.

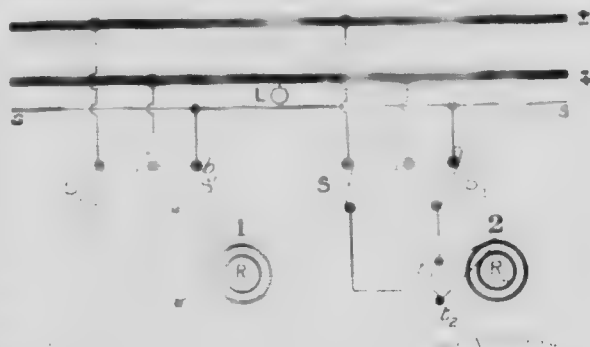
From the above it might be thought that the process of throwing an additional alternator into a circuit already supplied with alternate currents from other machines would be quite simple and somewhat as follows. First run the alternator that has to be switched in up to its proper speed, and excite its field magnets with the proper exciting current; then, when the field magnets are fully excited, simply close the switches which place the armature of the alternator on to the mains. In practice, however, an additional precaution must be taken, and the alternator must not be switched in until it is in the *same phase*, or nearly so, as the currents in the mains. If it is much out of phase, or, as it is usually expressed, *not in step* when switched in, then, although it would eventually get into step by means of the electrical actions and reactions already described, yet, during the time that this adjustment is taking place, violent fluctuations of current may arise which may cause serious trouble. But with rapid alternations a very small difference in the time at which the E. M. F. of the machine reaches its maximum will produce a great difference in the phase. For suppose the frequency of the alternations to be 100 per second, then, if the maximum is reached $\frac{1}{1000}$ th of a second too soon or too late, the phase

will be wrong by $\frac{1}{2}$ th of a full period, which would be a serious fault. But such a small interval of time cannot be observed directly, and the necessity for *phase indicators*, or *synchrosopes*, or *synchroscopes*, as they are called, which, being connected both to the mains and to the alternator not yet switched into circuit, show the relative phase at the moment when the phases are practically the same, so that an extra alternator can be safely thrown in. In the case of the method shown later, further precautions must be taken with the main supply. We shall therefore next describe the principle underlying, and the details of some of, these instruments.

Synchrosopes.

the generator to be *low-voltage* and which is not usually the case in modern stations, a practical synchroscope can be very simply arranged. The principle is shown in the accompanying diagram, Fig. 408.

In which R_1 and R_2 represent the slip rings of two low-voltage alternators **1** and **2**. The terminals t_1 and t_2 can be connected to the bus bar through switches s_1 and s_2 , but the other terminals t'_1 and t'_2 are connected to the movable tongue



the two-way switch s'_1 and s'_2 . In these switches the studs a are connected to the lower busbar, whilst the studs b are joined to a special synchronising glow lamp L between which and the lower busbar the synchronising glow lamp L is placed. Alternator **1** is represented as already connected to the busbar and disconnected from the synchronising bar. The movable tongue is connected to the lower busbar as far as possible to the lower busbar.

When the switch s_2 is closed, the lamp L will glow when the two voltages are in phase, and will be dark when they are in opposite phase. When the two voltages are in phase, the lamp L will glow, and the switch s'_2 can be changed over to the lamp L , which is supposed to be of suitable capacity. In the first case, being energised with double the normal voltage, it will glow brightly, and be nearly dark in the second case, since the voltage is only half the normal. The best method of applying the test is to commence with **2** running at

little too slow, but with its speed increasing by degrees. As it approaches the synchronous speed the lamp *L* begins to flicker perceptibly, the pulsations gradually get slower, and when their period is about three or four seconds the switch *S*'₂ is put over at the moment of *minimum* brightness. Unless the pulsation period is very long the lamp does not go quite black, because of the filament glowing for an appreciable time after the current has ceased.

If the switch is thrown over at the right moment, the machines, though not running with absolute synchronism, will fall into step because of the regulating action already referred to, and there will be no heavy equalising currents, for at the moment of switching in **2** they were almost exactly in phase. A little care and practice are, however, necessary to hit off

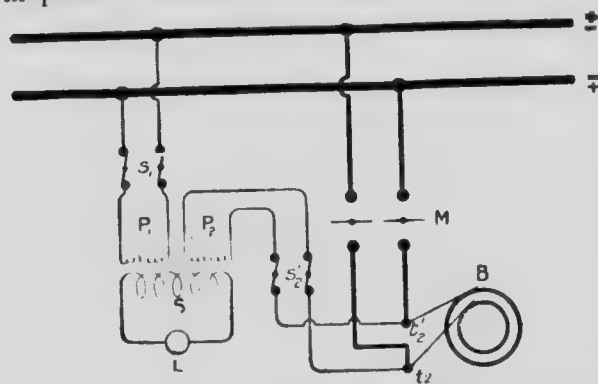


Fig. 409.—Connections for Synchronising High-Voltage Alternators with One Transformer.

this moment successfully. Instead of a lamp a hot-wire voltmeter may be used, to show when the brushes t_1 and t_2 are at the same potential.

With *high-voltage machines* it is obviously not possible to use a lamp in this way, because the lamp could not stand the pressure. Of course, a number of lamps in

series could replace the single lamp, but the arrangement becomes cumbersome when thousands of volts have to be dealt with. Instead, especially with stationary armatures, a single coil on each machine may be connected through proper switches to synchronising busbars provided with a phase-indicating lamp, as in Fig. 408. When the lamp shows that the machines are in step and running almost synchronously, the main switches putting the incoming machine on to the main busbars are to be closed.

Other methods depend upon the use of step-down transformers, by which the high voltage may be reduced to a pressure convenient for a glow lamp to be used as an indicator. For instance, with high voltages the lamp *L* of Fig. 408 may be replaced by the fine wire coil of such a transformer, with the lamp placed in its secondary circuit, which would be so wound as to give the maximum voltage the lamp can take when the alternators are in series. The phenomena already described will be observed, and the proper moment for switching on with the machines in phase similarly indicated.

Another method consists in having the synchronising transformer wound with two similar primary coils P_1 and P_2 (Fig. 400), one of which P_1 is connected through the double-pole switch S_1 to the busbars, and the other P_2 is connected through the similar switch S_2 to the terminals t_2 and t'_2 of the incoming machine B . The secondary S of this transformer is in circuit only with the indicating lamp L . The primaries P_1 and P_2 are so connected to the busbars and the terminals of B that when the machine is in phase with the busbars the currents in the wires flow in opposite directions round the core of the transformer, and therefore, since these currents will be equal if the voltages have been adjusted, the two magnetising effects will cancel one another, and there will be no flux through the iron as long as the equality of phase is maintained. During this period, therefore, the lamp L will receive no current, and will either be quite dark or be glowing only dimly. As before, it is at this moment, when the pulsations are long and the lamp is at its minimum brightness, that the main switch M is to be closed and the machine B thrown on to the busbars.

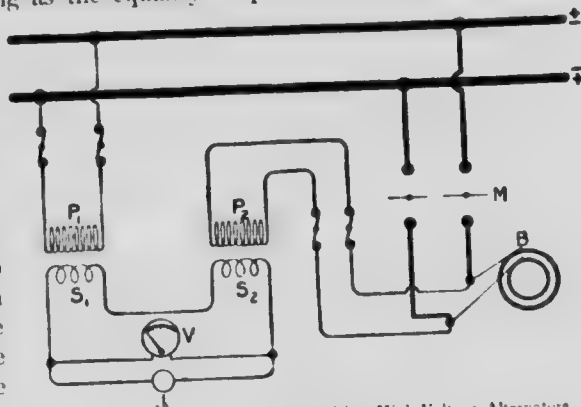


Fig. 400.—Connections for Synchronising High Voltage Alternators with Two Transformers

Modifications of this method are possible. Instead of using the full pressures of the busbars and terminals for the primaries P_1 and P_2 of the synchronising transformer, the pressures produced by single coils of the different alternators may be employed. In this case the terminals of these single or synchronising coils are most conveniently taken to a special panel or switchboard, where switches are arranged for throwing the coil of one of the loaded alternators in circuit with P_1 , whilst the coil of the incoming alternator is connected to P_2 . The other details are similar to those already described, but of the two methods the former is much more frequently used, for it dispenses with the additional complication of the special leads to one of the coils.

Still another method consists in using two transformers with their primaries P_1 and P_2 (Fig. 410) respectively in circuit with the busbars and the terminals of the incoming machine B , and their secondaries S_1 and S_2 in series with one another and with the synchronising lamp L . The secondaries can be so joined that either (a) there is no current in their

circuit when n is in phase with the busbars, or (b) there is a maximum current in this circuit when the phases coincide. The moment for switching on will be when the lamp is dimmest in case (a) and when the lamp is brightest in case (b). Either of these cases can also be arranged for with the connections shown in Fig. 409.

For synchronising purposes an under-run low candle-power carbon filament lamp is better than a high candle-power one, as the lag of the candle-power behind the voltage increases with the candle-power of the lamp, and also the eye can more readily estimate changes of brightness if it be not dazzled and fatigued periodically by a brilliantly glowing filament. With a metallic filament lamp the lag is much less, and if such a lamp be used the period of minimum brightness when near synchronism may be replaced by a longer or shorter period of absolute blackness. If this happens the arrangement (b) above referred to should be employed, for with it the moment for switching on can be more exactly estimated. To minimise possible errors either in place of the lamp or in conjunction with it, a synchronising voltmeter v is frequently used, as shown in Fig. 410. The voltmeter must be dead-beat, and one of the hot-wire types is very often employed. It is true that in such a voltmeter there is a certain amount of lag, but this has been found to be less objectionable than the inertia of the moving parts of most of the usual voltmeters. The period for switching should be arranged to be when the index is at its maximum deflection.

The synchroscopes or phase indicators so far described have been for single-phase currents, but can be used for polyphase currents if they are placed on one of the phases only. For, if one phase in each machine be in step, the other phases must be so likewise, because they are rigidly connected inside the machines, and cannot change their phase relations, though, as will be shown later, the order in which the phases follow one another must also be watched. The above synchroscopes, however, have a serious defect in common—namely, that they do not convey directly any information as to whether the incoming machine is running a little too fast or a little too slow, and it is far better to switch on in the latter than in the former case. To get over this difficulty it is noted (see page 398) that the experiment is best started with the incoming machine purposely running too slow and being speeded up.

It would, however, obviously be much better to have an arrangement which, besides showing when the phases coincide, would also give the additional information referred to. Several such devices have been designed for three-phase alternators, and Fig. 411 shows diagrammatically a method used for many years by Messrs. Siemens and Halske. Three alternators, I., II., and III., "star"-wound for three-phase currents, are indicated at the bottom of the figure, but to avoid confusion only one (No. I.) is

shown connected to the multiple contact three-phase switches A and B. The positions of the omitted connections, however, are clearly indicated by corresponding letters on the studs of the switches and at the alternators. The unmarked studs are supposed to be connected to the busbars (not shown), and the arms of the switches are supposed to join any stud upon which one of them is placed to the adjoining circular arc. There are three synchronising lamps L_1 , L_2 , and L_3 arranged round a dial, and two voltmeters V_1 and V_2 . Lamp L_1 and voltmeter V_1 are placed in parallel across

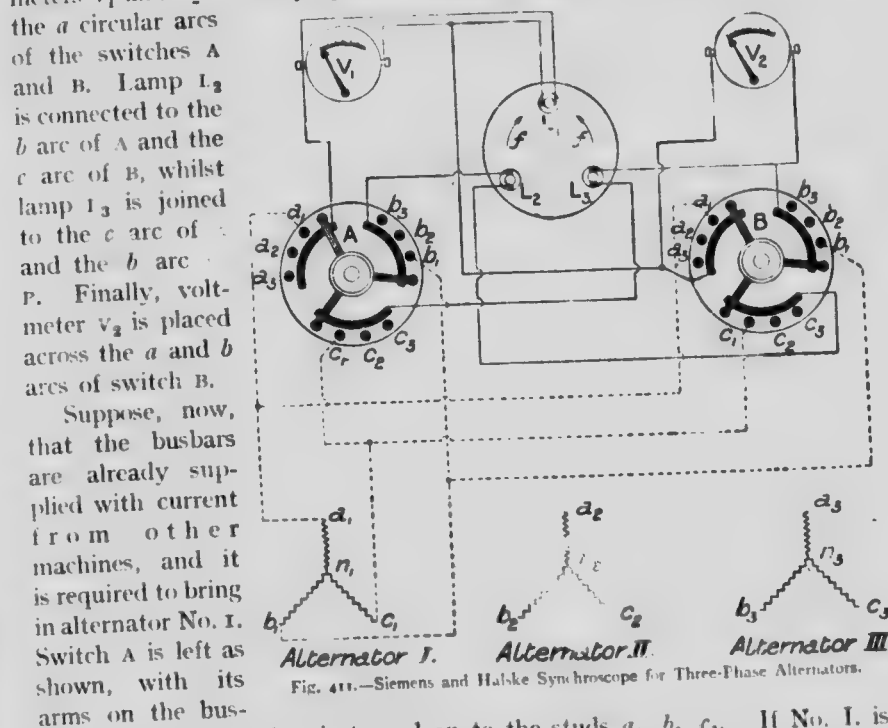


Fig. 411.—Siemens and Halske Synchronoscope for Three-Phase Alternators.

Suppose, now, that the busbars are already supplied with current from other machines, and it is required to bring in alternator No. I. Switch A is left as shown, with its arms on the busbar studs, but switch B is turned on to the studs a_1 , b_1 , c_1 . If No. I. is in phase with the busbars and running synchronously, the lamp L_1 will not light up, and V_1 will not deflect, whilst L_2 and L_3 will glow brightly, and voltmeter V_2 will indicate the pressure of one phase of No. I. On first closing the switches, however, the chances are very great against the above conditions being fulfilled, for usually No. I. will not be running synchronously. In this case the lamps will light up and be extinguished in succession, and the order of extinction will travel round the dial in a clockwise or a counter-clockwise direction, according as the incoming machine has a periodicity slightly lower or slightly higher than those already on the busbars. Thus the direction f of extinction

shows at once whether the incoming machine is running too slowly or too quickly.

As the speed of the incoming machine more and more nearly approaches synchronism, the extinctions travel more and more slowly round the dial, and the main switches throwing the alternator No. I. on to the busbars are to be closed when the extinctions are travelling quite slowly round, preferably in the clockwise direction, and when the lamp L_1 is dark and the lamps L_2 and L_3 equally bright.

The connections of a synchroscope used at one time by the Niagara Falls Power Company are shown in Fig. 412. The power supply is two-phase, and in the lower part of the figure there are two sets of busbars

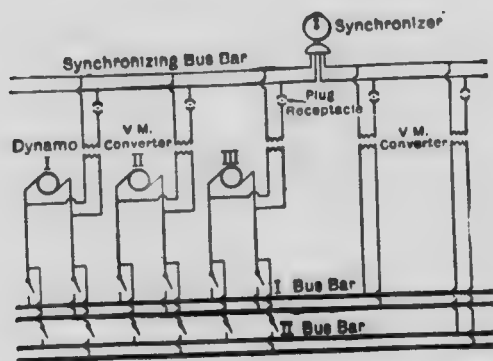


Fig. 412.

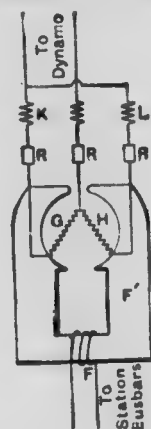


Fig. 413.

Connections of synchroscope used by the Niagara Falls Power Company.

I. and II., one set for each of the two phases. The synchronising busbars are also in two parts, one on the right for the main busbars, to either of which it can be connected through the secondaries of the voltmeter transformers or converters VM by inserting a plug in the corresponding lead. The other part is for connection to the phase of the incoming dynamo which it is desired to synchronise with one of the busbars. This connection is also made through a step-down voltmeter transformer by inserting a plug.

The synchroscope has four terminals, which are connected, as shown, to the two parts of the busbars. It is a single-phase bipolar induction motor (*see* page 622, Vol. I.), and is shown diagrammatically in Fig. 413. The stator F' is a laminated bipolar field magnet of the overpole type, and it is energised by the coil F , which is connected to one of the station busbars as shown in Fig. 412. The rotor is a split-phase rotor, having two coils G and H drum wound at right angles to one another. These coils receive current through the slip rings $R R R$ from the incoming dynamo. The

middle ring is connected to the common junction point of the coils and one lead, whilst the other ends are connected to the other lead, one through an inductive resistance K , and the other through a non-inductive resistance L . By properly proportioning the inductance and resistance of K and L the currents in G and H are made equal in magnitude, but differing in phase by a quarter-period. Therefore, if the rotor be held fixed, these currents produce the usual rotating field, whilst the field of the stator is a simple alternate field. If the sources supplying currents to the stator and rotor are in absolute synchronism and coincide in phase, the mechanical forces produced by the interaction of the magnetic fields will be balanced, and the rotor will come to rest with the field of H coinciding with the field of the stator. Another position of rest will be found 180° from the first position, when the synchronism is perfect and the phases are opposite. If, however, the sources are nearly but not quite synchronous, the rotor will rotate slowly, and at a rate nearly equal to the difference of the frequencies, either clockwise or counter-clockwise, according as the incoming machine is lagging or leading. An indicator moving over a dial is attached to the shaft of the rotor, and is fixed to stand upright when the phases coincide. The meaning of the two directions of rotation is also clearly marked on the dial, and the incoming machine is to be adjusted until the indicator is rotating quite slowly, and is to be switched on to the main busbars by



Fig. 414. Busbar Connections of Synchroscope.

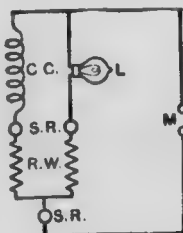


Fig. 415. Alternator Connections of Synchroscope.

the switches shown in the lower part of Fig. 412, when the indicator is vertical and passing through the zero position.

A motor synchroscope was designed independently by Messrs. Everett Edgcumbe and Co., of London. In a recent form of this instrument (Fig. 417) the stator is supplied with a single-phase current from the busbars, as shown in Fig. 414, where R is a resistance and $S.W.$ the stator winding. The rotor is supplied with two-phase currents from a single phase of the incoming machine, the two-phase currents being obtained by phase-splitting the single phase, as shown in Fig. 415. The coils $R.W.$ (Fig. 415) of the rotor winding, at right angles to one another, are in parallel on the leads from the machine M , but one of these coils has in series with it a non-inductive lamp resistance L , whilst the other has a choking coil $C.C.$ in series with it. The currents in the second coil, therefore, lag behind the currents in the first, and the two give a rotating field, as in the rotor of the Niagara synchroscope described above. The instrument is wound for 100 volts, and therefore, for high-voltage synchronising small step-down transformers

must be used, as shown in Fig. 416. As only about one ampere is required from each source, quite small transformers will suffice. In addition, an ordinary synchronising lamp can, if desired, be placed across the two sources of current, as shown in the figure.

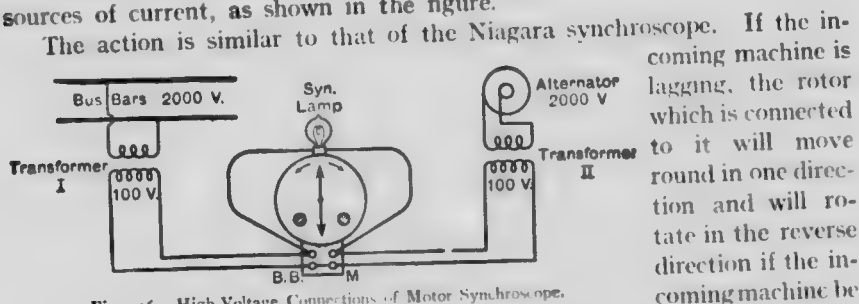


Fig. 416.—High-Voltage Connections of Motor Synchronoscope.

The action is similar to that of the Niagara synchronoscope. If the incoming machine is lagging, the rotor which is connected to it will move round in one direction and will rotate in the reverse direction if the incoming machine be running a little too fast. The front of the instrument is shown in Fig. 417. The dial, about 12 inches in diameter, is surmounted by the synchronising lamp when one is employed, and the needle attached to the shaft of the rotor moves over it. Since the motor has four poles it is easy to arrange for this needle to be vertical whenever the phases coincide, and it is then a matter of indifference which end of the needle is uppermost. It is when the needle is in the vertical position and rotating quite slowly that the incoming machine is to be thrown in.

The dark disc in Fig. 417 may appear illuminated with either green or red light. It is in front of a lamp between which and it one or other of two coloured glasses can be interposed. When the needle is rotating clockwise the red glass is shown, whilst for the opposite rotation the green glass appears. It is thus quite easy to see from a distance whether the incoming machine is running too fast or too slow.

In a more recent development of the Everett, Edgumbe synchronoscope the slip rings necessary to carry a current into a moving rotor are abolished, the rotor coil being replaced by a single fixed coil surrounded by four other coils

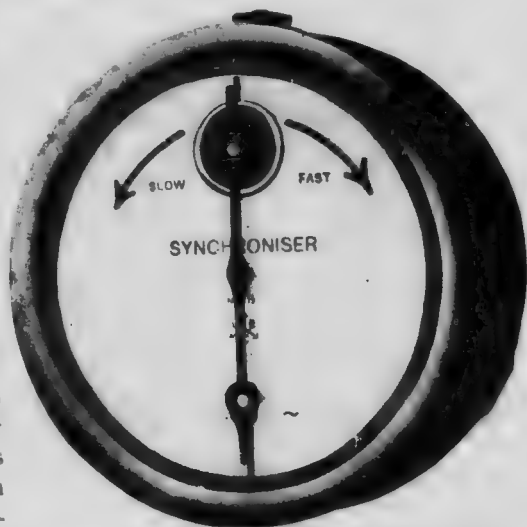


Fig. 417—Everett, Edgumbe & Co.'s Motor Synchronoscope.

which take the place of the stator in the synchroscope just described. The connections are as shown in Fig. 418, the difference between these and the other connections being that the stator is now shown as receiving at BB a single-phase current from the busbars, and the fixed coil which takes the place of the rotor is shown as receiving at M a single-phase current from the incoming machine. The difference, however, is immaterial, as the phase of the stator current is split for the production of a four-pole rotating field, one phase being taken by the coils $w_1 w_3$ and the non-inductive resistance, and the other by the coils $w_2 w_4$ and the inductive reactance or choking coil c c. The coils w_1 and w_2 are so connected that their fields coincide, producing a vertical field through the space occupied by the central coil. Similarly the coils w_3 and w_4 produce a horizontal, but lagging field. None of the coils has any iron core.

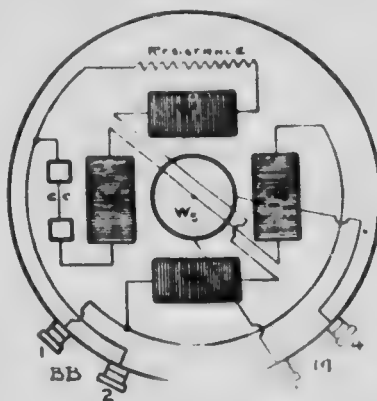


Fig. 418. Connections of Slip Rings.

with no

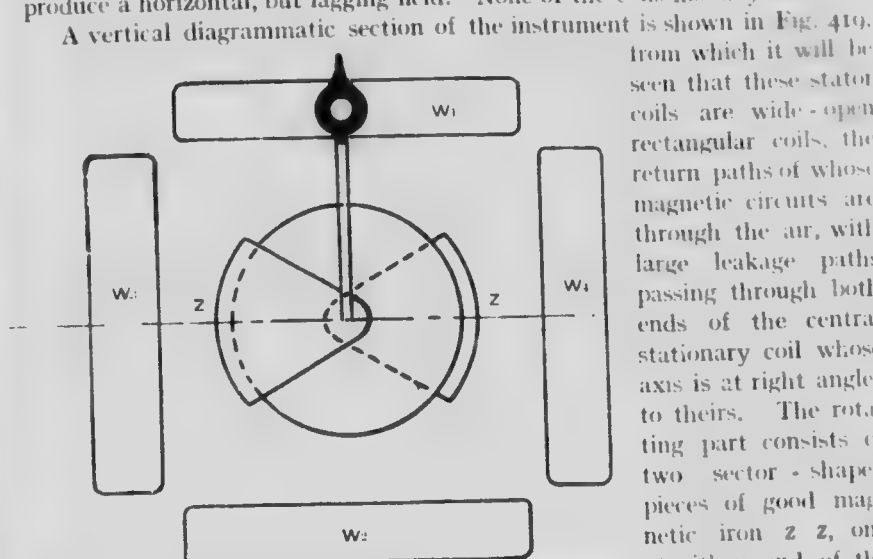


Fig. 419.—Vertical Diagram of Everett, Edgumbe & Co.'s Synchroscope with no Slip Rings.

A vertical diagrammatic section of the instrument is shown in Fig. 419, from which it will be seen that these stator coils are wide-open rectangular coils, the return paths of whose magnetic circuits are through the air, with large leakage paths passing through both ends of the central stationary coil whose axis is at right angles to theirs. The rotating part consists of two sector-shaped pieces of good magnetic iron $z z$, one at either end of the axle, set 180° apart, that is on opposite sides of the axle. Their positions are more clearly indicated in Fig. 420, which shows a horizontal cross-section through the axle and in which $w_1 w_3$ are two of the stator coils, R the

rotor coil, now stationary, and $z z$ the sectors, one in front of, and the other behind, the rotor coil R .

The effect of the current in the coils $w_3 w_4$ is to produce a rotating field through and over the sectors which, if it were not for the iron sectors $z z$ would rotate in vertical

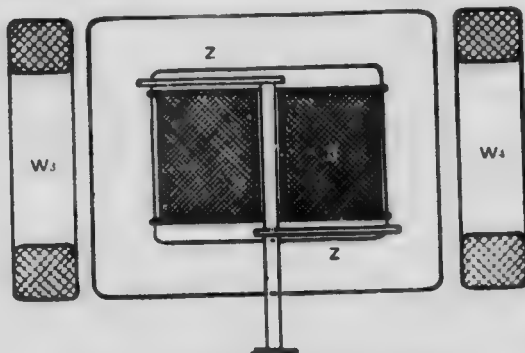


Fig. 420.—Horizontal Cross-Section of Synchroscope.

planes round the horizontal axis of the central coil. The unsymmetrical positions of the two magnetic sectors, however, twists this field from these planes in which it would be simply at right angles to the field of R , and gives it a skew direction, in which it sweeps through and over the sectors, which will therefore tend to be dragged round as is the magnet in Fig. 588, Vol. I., for these sectors may be regarded as independently magnetised by the currents in R . The single-phase current in R , on the other hand, though it will pump an oscillating field through and over the sectors, will not tend by itself to rotate them, if everything is symmetrical, as it is fixed in position.

We thus have (i.) a rotating field due to the coils w sweeping through and about the sectors; (ii.) an oscillating field, radially outwards (or inwards) passing through the sectors; and (iii.) the pivoted system, including the magnetic sectors, free to rotate under the forces due to the interaction of these fields and the magnetic flux of the sectors, due to their position in these fields. If the mutual effects of these fields are examined as superimposed both in time and space, it will be obvious

that the lagging field of $w_3 w_4$ will more nearly coincide in its time of maximum with the field of R if the original single-phase currents are in phase than will the field due to $w_1 w_2$, and that in this case by the time the field of $w_1 w_2$ is at a maximum the current in R will be nearly, if not

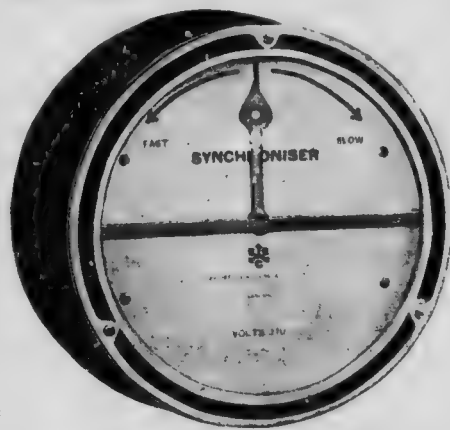


Fig. 421.—Everett, Edgumbe & Co.'s Synchroscope with no Slip Rings.

quite, zero. Consequently, when the original currents are in phase the sectors will be held most strongly in the horizontal position with the needle vertical. If the original currents are slightly out of phase the sectors will be dragged round clockwise or counter clockwise, according to the direction of the phase difference, and thus the rules for using the synchroniser will be the same as in the preceding cases. The external appearance of the instrument is depicted in Fig. 421.

In the rotary synchronoscope of Messrs. Ferranti, Limited, both stator and rotor have laminated iron cores, the latter being mounted on a strong spindle running in ball bearings. By the use of iron cores as in some of the instruments already described, the working forces are much greater, and there is less possibility of sticking and of wrong indications. The connections of the Ferranti synchronoscope are given in Fig. 422, in which it will be seen that there is a single-phase current in the stator coils *s s*, taken from the busbars through the terminals 1 and 2 at *B B*. The current is introduced into the rotor from the terminals 3 and 4 at *M*, through three slip rings; the rotor has a two-phase winding, the two parts of which are in parallel, one through the choking coil *C*, and the other through the practically non-inductive lamp resistance *L*, which may be used to illuminate a dial, as in the synchronoscope shown in Fig. 417. The rotating field of the rotor interacts with the

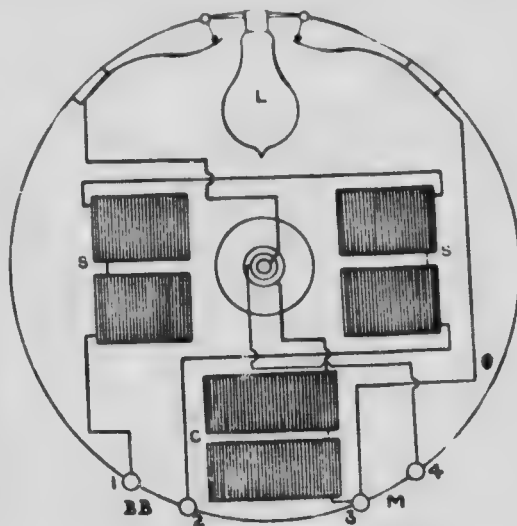


Fig. 422.—Circuits of the Ferranti Synchronoscope.



Fig. 423.—Ferranti Rotating Synchronoscope.

alternating field, fixed in space, of the stator in the manner already explained, and with similar results.

The exterior of the instrument is shown in Fig. 423, with a synchronising lamp added. Its connections to two typical high-pressure three-phase systems are given in Figs. 424 and 425. In Fig. 424, generators G1 and G2 are shown synchronised with the busbars. The busbars are

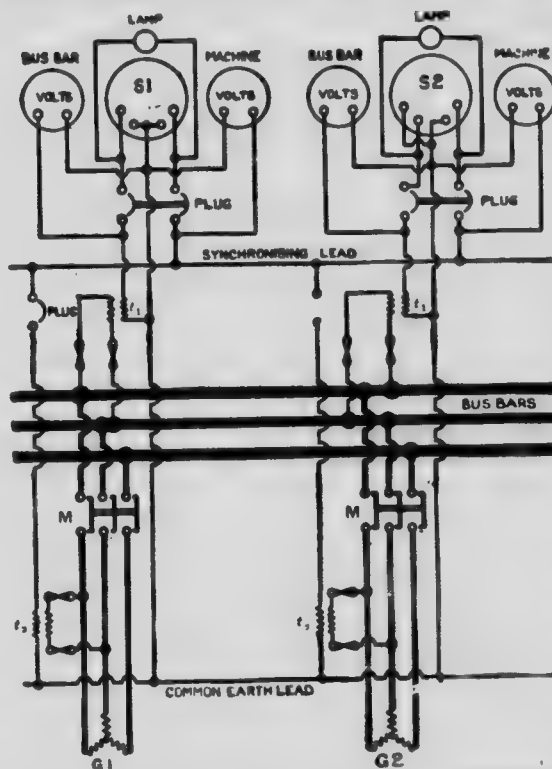


Fig. 424.—Connection of Synchroscope for Synchronising with Busbars.

connected to the left-hand terminals (1, 2, of Fig. 422) of the synchroscope through the potential transformer t_1 , whose primary is bridged across the two upper busbars, and its secondary connected to the terminals named, with the left-hand, or busbar, voltmeter in parallel. Another potential transformer t_2 , has its primary inserted across two of the mains from the generator between the generator and its main switch M. The secondary is connected to the "synchronising lead" through a plug switch, and to the "common earth lead" direct; the two leads named are connected to the right-hand terminals (3, 4 of Fig. 422) of the

synchroscope with the "machine" voltmeter in parallel. With the plug switches both closed and the main switch M open, the generator is in the position for synchronising with the busbars. The second synchroscope S2 is introduced into the diagram merely to show an alternative method of joining up the synchronising lamp. In S1 this lamp is placed across the terminals 1 and 4, of Fig. 422, and with the transformer connections, as shown, this means that the lamp will have no voltage, and, therefore, should be extinguished at the moment of synchronism. In S2 the lamp is across terminals 2 and 4, which are not in the same electrical positions as 1 and 4 in the S1 connections, the phase

of 2 for s2 differing from 1 for s1 by 180° . The lamp therefore gets double voltage at the moment of synchronism, and glows brightly then. One pair of terminals of the synchroscope also having had its connections reversed, the needle still indicates synchronism by its upright position.

In Fig. 425, three generators, G3, G4, and G5, are synchronised with one another with no potential transformers on the bus-bars. This necessitates

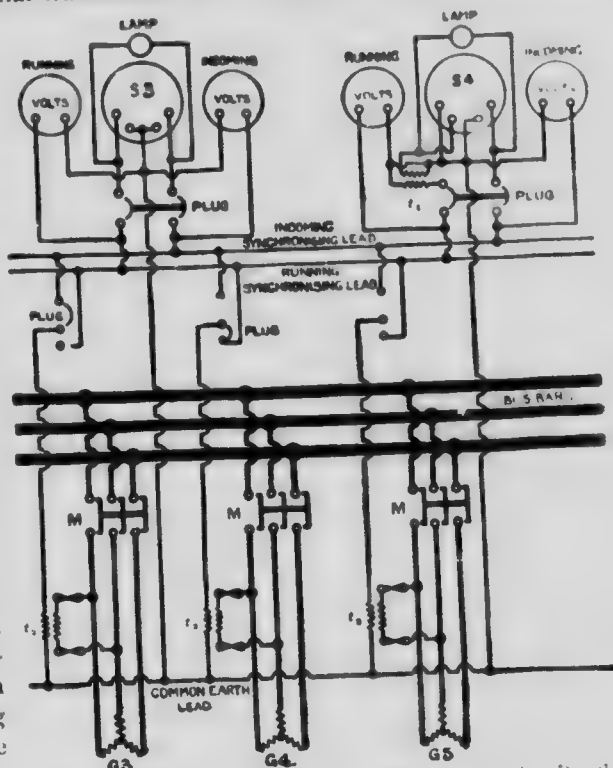


Fig. 425.—Connection of Synchroscope for Synchronising Machines Directly

In this diagram also two synchrosopes, S3 and S4, are shown for the same purpose as in Fig. 424, namely, one, S3, with the lamp connected so as to be dark at the moment of synchronism, and the other, S4, so that its lamp is bright at that moment. To keep the phase relations right, a small equal ratio transformer, T, is inserted with its primary across the terminals of the "running" voltmeter, and its secondary in parallel with the terminals 1 and 2 of the synchroscope; the lamp terminals are across 2 and 4, as in S2 (Fig. 424). By this device the lamp gets double voltage, and the pointer of the synchroscope is upright at the moment of synchronism.

In these instruments a useful device is added, if required, in the form of relay contacts, closed by a balanced arm working between stops and driven loosely by friction from a sleeve on the spindle. When the spindle is rotating in one direction, the arm is held so as to close one pair of contacts; it closes the other pair when the spindle rotates in the opposite direction. The arm thus acts as the line circuit of a relay, the contacts being in local circuits which, when closed, are used to give pre-arranged signals at any part of the station; for instance, to the driver at the stop-valve of the engine, and also to the operator, if he cannot see the synchroscope. The arm-sleeve working this arm can be, and is, used to interpose the green or red glass between the lamp and the window in the dial on those instruments in which a coloured visual signal is given, as explained already.

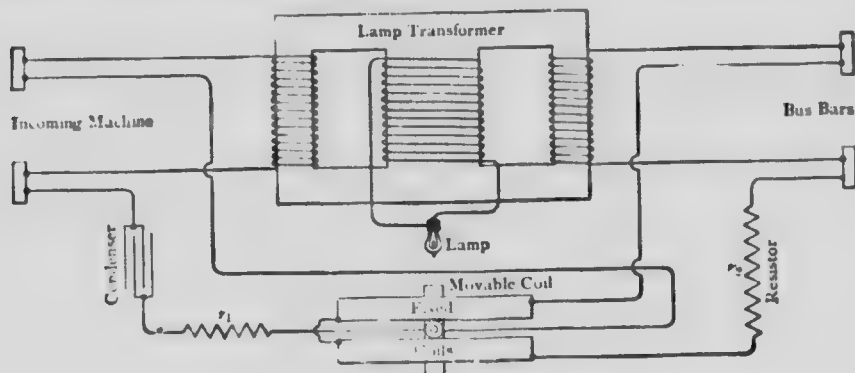


Fig. 426.—Connections of Weston Synchroscope.

Another form of synchroscope or synchroniser makes use of the principle of the *electro-dynamometer* already explained (see pages 732 to 734, Vol. I.), in connection with the measurement of continuous currents, and also in connection with the measurement of alternate currents (*ibid* page 767), A.C. power (*ibid*, pages 801 *et seq.*) and power-factors (*ibid.*, pages 809 *et seq.*).

When adapted for use as a synchroscope, both coils of the electro dynamometer movement are wound with fine wire, one of them being placed as a shunt across the terminals of the incoming machine and the other across the busbars or the terminals of the machine already running. In the Weston synchroscope, a diagram of the connections of which is given in Fig. 426, the movable coil is put on the incoming machine terminals and the fixed coils on the busbar terminals of the instrument. The principle underlying the working of the instrument is that there will be no torque in the moving coil when the currents in the two circuits are in time-

quadrature. To secure this, when the phases to be compared are synchronous a condenser is introduced into the moving-coil circuit and an inductive resistance into the fixed-coil circuit. The angle of lead in the first circuit will then be given (see page 547, Vol. I.) by the equation

$$\tan \lambda_1 = \frac{1}{K} \frac{1}{p r_1} \quad (1)$$

or when

$$\cot \lambda_1 = K p r_1 \quad (2)$$

and the angle of lead in the second circuit will be given (see page 543, Vol. I.) by the equation

$$\tan \lambda_2 = \frac{p L}{r_2} \quad (3)$$

The two angles will be complementary, that is they will differ by 90° when

$$\frac{p L}{r_2} = K p r_1$$

that is when

$$L = K r_1 r_2 \quad (4)$$

The angles of lead and lag are in each case measured with reference to the phase of the terminals of the circuit, and, therefore, if the condition in equation (4) be fulfilled the currents in the instrument will be in time quadrature when these phases coincide. It must, however, be noted that the currents will also be in time quadrature if the phases are in opposition, for in that case one phase is moved round 180° , which still leaves the angle between lag and lead $= 90^\circ$, but in the opposite direction. This is important in connection with the theory of the instrument, as will presently appear.

A view showing the interior of the instrument is given in Fig. 427, and the external appearance is shown in Fig. 428. The fixed coils are the two large horizontal coils, which are separated a little from one another, so that the axle of the vertical movable coil can be passed between them. This vertical coil has its centre at the middle of the common axis of the fixed coils, and is sufficiently small to rotate inside the latter. Its axle carries the pointer, and when there is no torque between the fixed and movable coils the latter and its needle are held in the vertical position by two flat spiral springs, one at each end of the axle, and the nearer one of which can be made out in the figure. From what has been said above it will be understood that the needle stands vertical when the



Fig. 427.—Interior View of Weston Synchroscope.

phases at the terminals of the instrument either coincide or are in direct opposition.

If there be any difference of phase other than direct opposition, the pointer will be deflected right or left, depending on the phase difference, the voltages at the terminals, and the controlling torque of the spiral springs. The circuits are so joined up that when the incoming machine phase is lagging the deflection is to the left, and when it is leading the deflection is to the right. Therefore when the phase relations are changing slowly, the pointer will oscillate backwards and forwards fairly well in step with the phase changes if these be not too rapid.

It is at this stage that the use of the lamp which appears in Figs. 426 and 427 becomes apparent. The lamp is placed behind the black rectangle, which is seen in the middle of the scale in Fig. 428. It is connected to the secondary of the lamp transformer shown in Fig. 426, the two primaries of the transformer being connected one to each pair of terminals of the instrument. An examination of the circuits will show that when the primaries are in phase the lamp circuit will



Fig. 428.—The Weston Synchronoscope.

be energised, and that no magnetic flux will pass through this circuit when the phases are in opposition; in the latter case the lamp will therefore be dark, and the translucent scale will not be illuminated at this moment if the phases are changing with sufficient slowness. A little further consideration will show that if the incoming machine is too slow the scale and pointer will be illuminated chiefly when the latter is moving towards the left, and, on the contrary, when the incoming machine is too fast. It should be noted that, the pointers being behind the screen, it can only be seen when the lamp is lit up. Thus it follows that the direction in which the pointer appears to be moving indicates whether the incoming machine is "slow" or "fast." To prevent mistakes, these words are clearly shown on the translucent screen.

The inductive resistance or choking coil r_s , the lamp transformer, and the condenser, which are shown diagrammatically in Fig. 426, are all

contained in a case which is mounted on the back of the cover of the box and forms one piece of apparatus with the synchroscope. They are shown in position on their base plate in Fig. 429, in which R is the non-inductive resistance, T the lamp transformer, and C the condenser. In order that there may be the proper time quadrature between the currents in the two circuits when the phases coincide, it is necessary, as shown above, that

$$L = K r_1 r_2,$$

where r_1 and r_2 include the resistances of the movable and fixed coils, as well as the resistances respectively in series with them.

In some measurements made by Dr. Drysdale on an actual instrument, it was found that

$$\begin{aligned} K &= 1.08 \text{ microfarad} \\ &= 1.08 \times 10^{-6} \text{ farad} \\ r_1 &= 360 \text{ ohms} \\ r_2 &= 1.026 + 480 = 1.506 \text{ ohms} \\ K r_1 r_2 &= 360 \times 1.506 \times 1.08 \times 10^{-6} \\ &= 0.595 \text{ henry} \end{aligned}$$

whence

Also (by measurement) $L = 0.585$ henry.

which shows that the theoretical conditions for quadrature were very closely approximated to. The instrument is therefore within wide practical limits independent of frequency.

For this method of ascertaining the phase-difference for synchronising purposes it is claimed that the indications are infallible, and that its use is simple, as there is only one object (the moving pointer) to observe; also that it indicates exact synchronism within one degree of true phase-coincidence over a wide range of frequency and voltage.

Paralleling Alternators.—Even if the phase and voltage be right and the synchronism nearly perfect, care must be taken in throwing the incoming machine on to the busbars, so as to ensure that it picks up its load without disturbance whilst it is being pulled, as it were, into perfect step.

To overcome the possible difficulties one method consists in running the incoming alternator on an artificial load whilst adjusting its voltage and synchronising; it is then connected to the busbars and the artificial load gradually removed. This, however, increases the total load on the station whilst the new machine is being adjusted to its work, and delays

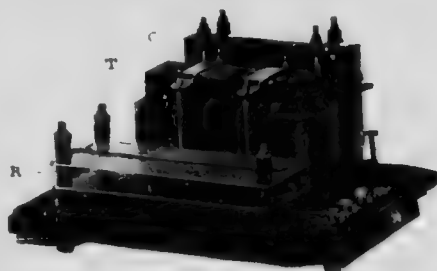


Fig. 429. Auxiliaries of the Weston Synchroscope.

the time when, by taking its share of the working load, it can relieve the other machines, which are probably overloaded. Several ways of overcoming this difficulty have been tried. For instance, instead of putting the machine after synchronising, etc., straight on to the busbars, an adjustable choking coil or reactance is interposed. As this reactance is reduced step by step, the exciting current is adjusted to keep the voltage equal to the P. D. of the busbars, with the result that when it is finally cut out the alternator is quietly taking its full share of the load.

A method of applying the artificial load is shown diagrammatically in Fig. 430. In addition to the ordinary busbars B_1 and B_2 there are two auxiliary bars A_1 and A_2 connected to an adjustable artificial load. There is also a synchronising transformer with its primary w_2 connected to $A_1 A_2$,

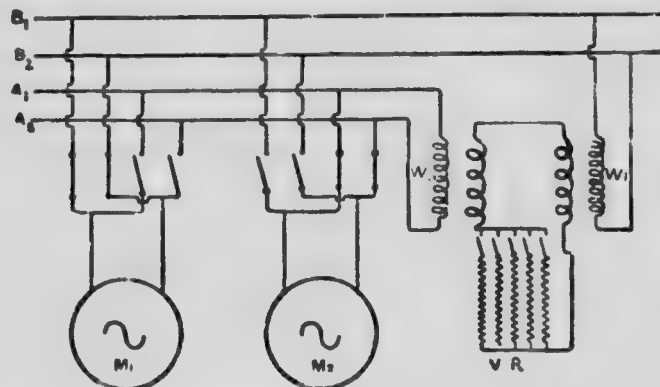


Fig. 430.—Connections for Loading Alternators whilst Paralleling

and with a variable resistance VR in its secondary circuit, which also includes the secondary of another transformer whose primary w_1 is connected to $B_1 B_2$. A lamp or voltmeter test is used to indicate synchronism. The machine M_1 is already on the busbars, and it is required to bring in the machine M_2 . To do this M_2 is run up to its proper speed and excitation on the bars $A_1 A_2$ with the artificial load in circuit. The secondary circuit of the transformer is then closed and the sections of the resistance removed step by step, whilst M_2 comes into perfect synchronism, when the artificial load can be thrown off and M_2 put on to the busbars.

Hunting.—With alternators directly coupled to reciprocating steam engines there is sometimes developed a troublesome phenomenon which is not so frequently experienced with belt-driven or turbine-driven alternators. The machines will run quite smoothly for a longer or shorter period, till it will be observed that the ammeters of the different alternators begin to swing, showing variations in the currents passing to the busbars. These swings gradually increase in amplitude, and as the feeder ammeters are practically unaffected, they indicate that heavy currents are passing between the machines. If the mischief is allowed to develop these currents become sufficiently large to cause pulsations in the P. D. of the

busbars, and sometimes to blow the fuses. The phenomenon is known as "hunting."

Various explanations have been suggested, but since the trouble sometimes develops quite gradually it seems to be in most cases a resonance effect caused by periodical disturbances, which happen to have a periodicity with a simple relation to the natural period of oscillation of the armature. The disturbance, once started, gradually increases, because of the recurrence of its cause at particularly favourable instants of time. Another explanation is that it may be due to interference effects caused by differences of wave form, and the superposition of the harmonic waves of shorter period than the principal wave. Considering the first suggestion, we know that the power is not given uniformly to a reciprocating engine by the steam, but in a series of impulses, and that therefore the driving moment on the shaft oscillates between maximum and minimum values, however the cranks may be set. If the period of this oscillation coincides with the period of free oscillation of the rotating parts, the angular velocity of the latter will oscillate about the mean value, and if these oscillations are not damped their amplitude may increase until it becomes dangerous.

This theory points to two different kinds of remedies. One is to alter the period of oscillation of the rotating parts, which can be done by increasing or decreasing the weight of the flywheel, and so changing its moment of inertia. The other method is to introduce some kind of damping device which will prevent the oscillations attaining a dangerous amplitude. For instance a choking coil inserted between the alternator and the busbars will have a damping effect, but in practice it is found that the inductance must be somewhat large to be effective, and this cuts down the p. d. by increasing the lost volts, and renders a heavier exciting current necessary.

Another mechanical cause of periodic disturbance may exist in the governor. For instance, if the governor be very sensitive, the fluctuations in the angular velocity of the prime mover may set up oscillations in the governor which, reacting on the conditions of running of the prime mover, may give rise to hunting. If this be found to be the cause it is easily remedied by making the governor less sensitive, by damping its motion with dashpots, or otherwise. With electrical governors the conditions become still more complicated, and resonance effects may be produced in other ways.

In considering the action of damping devices, it must be remembered that, as shown in the general theory of the parallel running of alternators (see page 395 *ante*), when a machine gets a little out of step with the busbars, the reactions set up tend to pull it into step whether it be leading or lagging. Therefore, if it were not for the recurrence of the disturbance with a periodicity which can produce resonance effects, the effect of any casual and temporary disturbance, if not too overwhelming, would soon die away. The oscillations produced by such resonance effects are usually

long-period oscillations, and as such are more difficult to handle than more rapid ones, which can often be damped down by mechanical devices.

A very simple method of electro-magnetic damping proposed by Leblanc

has been found effective. It will be best understood by reference to Figs. 431 and 432, which represent sections perpendicular to and through the shaft of a portion of a Hutin-Leblanc alternator built in 1806. It was of the revolving field type, and had an output of 480 kilowatts at a speed of 60 R. P. M., the periodicity being 40 $\sim$ and the pressure 3,000 volts. The magnet ring was 20 feet in diameter, and the air-gap clearance was only 0.32 inch. There were six slots per pole, but as the machine was for single-phase currents two of these were unwound. The special feature, however, was that each pole face was pierced quite close up to the gap by six holes A A, in which were placed solid copper rods 0.82 square inch in cross-section. These rods were clamped together at their ends by the copper segments s (Fig. 432), and thus very

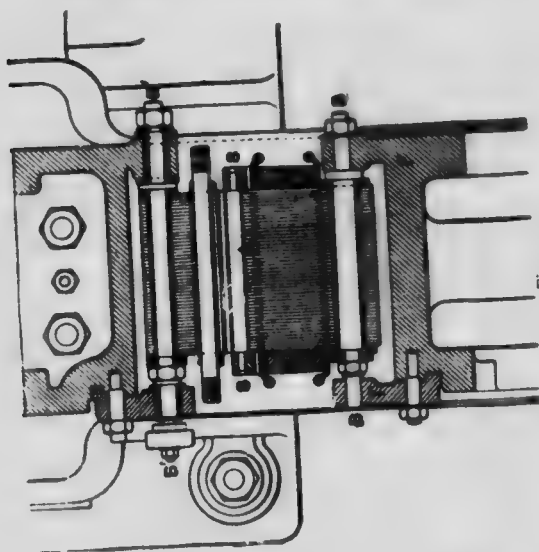


Fig. 432.

Sections of Alternator fitted with "Amortisseur" or "Inductor" (Fig. 431).

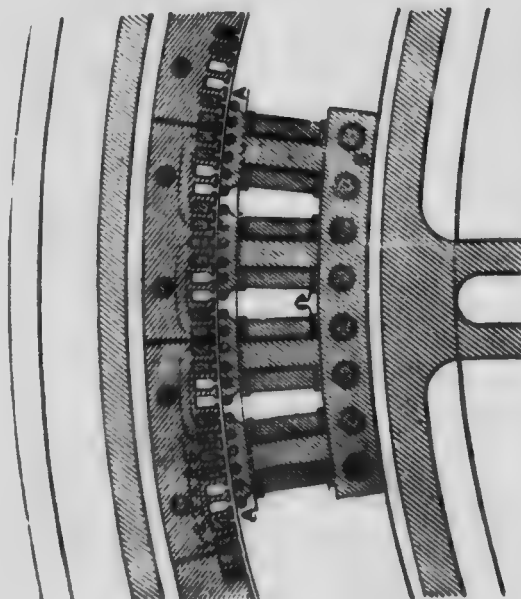


Fig. 431.

much resembled the copper conductors of the squirrel-cage rotor (Fig. 502, Vol. I.), of an induction motor. These closed copper circuits on the poles, by the inductive action of the currents induced in them, have been found to exercise a very decisive damping action, which prevents any hunting that may be started from developing to a dangerous extent. They were called by their inventor "*amortisseurs*" or "*damping*" circuits. In addition, they also help to bring the machine more rapidly into synchronism if it should be thrown on to the busbars slightly out of step.

The action of the damping circuits can be simply explained by reference to the theory of the induction motor. It will subsequently be pointed out that for such a motor to absorb power from the electrical circuits of the stator the rotor



Fig. 433.—Interpole Damping Circuits on a Revolving 1,000 KVA.

must run at a speed less than that corresponding to the angular velocity of the rotating field; in other words, there must be a certain amount of "slip" between the two. It can further be shown that if there be no slip there can be no currents in the rotor, and therefore no mechanical action; whilst if the slip be reversed—that is, if the rotor be forcibly driven at a speed higher than the synchronous speed

the machine will act as a generator and absorb mechanical power from the driver.

In our present case the speed of the rotating magnets when "hunting" is alternately too fast and too slow, and oscillates between limits with perfect regularity. Now, when it is too slow, the damping circuits, because of the magnetic flux due to the armature reaction, cause it to act as an induction motor taking power from the electrical circuits, which will tend to quicken it up to the normal speed. On the other hand, when it is running too fast the reaction of the damping circuits is a generator reaction, which absorbs additional mechanical power from the shaft, and tends to

slow down the speed to the normal. At normal speed the damping circuits are dead, and have no effect on the running of the machine.

It will be clear that these circuits very much increase the self-regulating action of alternators, which has been already referred to (see page 396), for with any deviation from normal speed they come into action and help to pull the machine back again into step. On the other hand, it is obvious that the cutting away of so much iron out of the pole must seriously increase the reluctance of the magnetic circuit, and therefore render more exciting power necessary, thus reducing the efficiency of the machine. In later machines, therefore, the damping circuits were



Fig. 434.—Inter-polar Damping Circuits on a Fixed Field Magnet.

removed from the poles and placed in the polar gaps, as shown in Fig. 43, which represents a portion of the revolving field magnet of a large Westinghouse alternator. It will be noticed that the field coils are held in their places by very substantial wedges slipped under the projecting tips of the pole pieces. These wedges are made of gun-metal or other non-magnetic but conducting material, and, in addition to their mechanical action, they form closed conducting circuits, which act as the damping circuits of Leblanc.

Damping circuits can be placed similarly on the fixed magnet of alternators with revolving armatures, for relative motion is all that need be considered. In Fig. 434 is shown a portion of the fixed magnet of a machine built by the General Electric Company of Schenectady, in which copper strips, whose shape can easily be made out and fitted under the pole tips to prevent hunting. The expansion of them

action is the same as that given above for revolving field magnets similarly fitted.

It is obvious from the above explanation that if the pole pieces or shoes are solid, the iron of the pole piece will supply damping circuits, but on account of the higher resistance of iron, the damping torque will not be so great under similar conditions of disturbance as when copper circuits are available. With laminated pole pieces the damping currents would be still further diminished, but may be set up deeper down in solid cores or even in the field coils. Such currents, however, cannot be as effective as the currents in the "amortisseur" circuits.

In conclusion, it should be pointed out that one of the most fruitful sources of hunting, namely, variable driving torque for different positions of the crank, is absent in steam turbines, and, as a consequence, turbo-alternators seldom, if ever, exhibit the phenomenon of hunting when run in parallel.

IV.—PUBLIC SUPPLY STATIONS

Types of Stations: Classification.—The choice of the site for, and the planning of, a generating station so that it shall be a financial success is essentially a problem for the engineer as distinct from the designer and inventor of machinery and apparatus. During the past thirty years the problems involved have attracted the attention and occupied the time of some of the foremost engineering minds of the period, and therefore, since conditions are infinitely varied, hundreds of stations have been erected with almost every possible variation, reflecting the peculiarity of the special conditions and the idiosyncrasies of those responsible for their elaboration. So rapid has been the development, that many of these have long since become obsolete, some have had their machinery scrapped two, three or four times, and their whole plan re-modelled, whilst the demand for larger and larger stations has throughout been very insistent. It would, therefore, be quite impossible to describe even a small proportion of the stations which have been at work during the period named, and some sort of classification is necessary, so that we may deal with general types of generating stations only with sufficient detail as to

which have been expected to last for a long time, and which are of the type which cannot be formed

which are formed entirely with the object of

which are formed at first and most commonly

which are formed to take the energy from

which are formed to take the energy from

which are formed to take the energy from

which are formed to take the energy from

which are formed to take the energy from

which are formed to take the energy from

which are formed to take the energy from

which are formed to take the energy from

(ii.) Alternating current stations:

- (a) Moderate voltage.
- (b) High voltage.
- (c) Extra high voltage.

There might also be a cross-classification, according as the station was to supply energy (a) at constant pressure, or (b) at constant current, but the latter has been comparatively so little used in practical work that this cross-classification would, at present, not be of much importance.

At one time in the early period of development the above classification would have been the most convenient, for in those days engineers had to drive their generators with whatever kind of prime mover was available, though it might have been originally designed for quite a different purpose. Under these circumstances, it was the generator which might be said to fix the type of the station.

This has now been modified, at least partially, and a more convenient classification at the present time will be rather as follows:—

1. *Steam-driven stations*, with
 - (a) Slow-speed generators.
 - (b) Moderate-speed generators.
 - (c) High-speed or turbo- generators.
2. *Gas or oil-driven stations*.
3. *Water-power (hydro-electric) stations*, with
 - (a) Low head or small water pressure available.
 - (b) High head or great water pressure available.

Even this classification can only be regarded as tentative, and, at the highest, as a convenient one, for stations exist in which the classes of generators which give rise to the three sub-divisions of No. 1 are found working side by side; and, again, it is not unusual to find in hydro-electric stations (No. 3), steam plant installed, either to take the whole load if the water supply be shut down by climatic influences (frost, etc.), or to assist the water-power plant over the load peaks, or when the supply of water, owing to seasonal variations, falls below the requirements of the station.

Load Curves and Diagrams.—In setting about the design of a generating station for the transformation of any of the sources of energy just referred to, the first problem to be faced is the ultimate utilisation of the energy—a problem which has been referred to in general terms in the introductory remarks (*see* pages 370 and 371) at the beginning of this chapter. In the general case, where the energy is not required for a clearly-defined object, easily amenable to calculation, the engineer should make a special study, not only of the industrial occupations, but also of the social peculiarities of the people in the area in which it is proposed to utilise the electric energy produced. As a rule, these lines of investiga-

tion will be found to be closely interwoven. How far, for instance, do the industries of the locality require power for their efficient exploitation, and how far is the necessity for this power likely to take the form of a demand for electric power? Then again, what influence will the social habits and circumstances of the inhabitants have upon their demand for electric power for lighting purposes—domestic, public and industrial, and for electric traction—in their daily avocations?

On these and numerous other points the data will differ infinitely in different localities, and it is not possible to give figures generally applicable. The data and records are usually set forth in curves, the vertical ordinates of which indicate the load in kilowatts and the horizontal ordinates the time. The curves are known as "load curves" or "load diagrams," and are replete, to those who can read them aright, with details

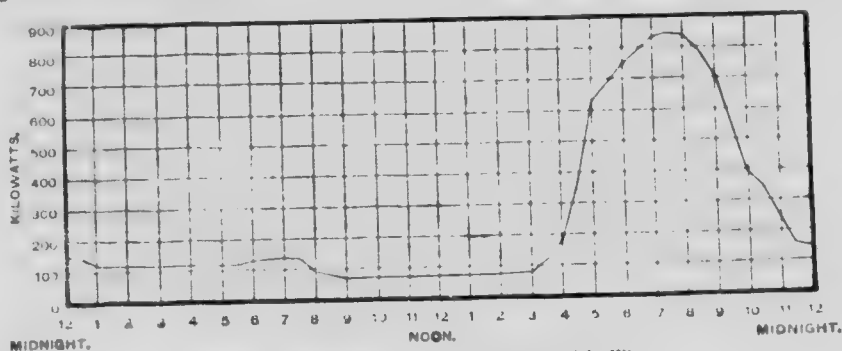


Fig. 435.—Load Diagram for a "Lighting" Load in Winter.

of the social and industrial conditions of the districts to which they refer. A few examples will make this clear.

In Fig. 435* such a curve for a station loaded almost entirely with a lighting load is shown. The curve, which is for a mid-January day, starts from 12 midnight on the left hand side and extends to the following midnight on the right-hand side through the intervening twenty-four hours. Up to 3 o'clock in the afternoon, with the exception of a slight rise at the breakfast period between 6 a.m. and 8 a.m., the curve is almost level and very low. At 3 p.m. it begins to rise, and rises rapidly between 4 p.m. and 5 p.m., when darkness closes in. There is a lower rise from 5 p.m. till about 7 p.m. after which the curve falls slowly until midnight. Such a curve is obviously a curve of the residential part of a district, with very little shop lighting, and with no power load worth mentioning during the hours of daylight.

* This and some of the following curves are taken from papers in *The Electrician* (1911) on the Electric Supply of London by Mr. Pearson.

The importance of some of the uses which may be made of such a curve are shown in Fig. 436, which is the load diagram for another district in London—Fulham—for a December day. In this instance the difference between the high-peak load in the early evening and the day load up to 4 p.m. is not so marked as in Fig. 435, showing the existence of a power load during the day, and additional evidence of this power load is given by the depression during the dinner hour, between 1 p.m. and 2 p.m. What is especially interesting in this diagram is that the capacity of the plant which has to be run during different periods is shown by the dotted line, from which it will be seen that 600-kilowatt plants were running from 12 midnight to 1.40 a.m., at which time the running plant was reduced to 300 kilowatts, which served the purposes of the station until 5.30 a.m.,

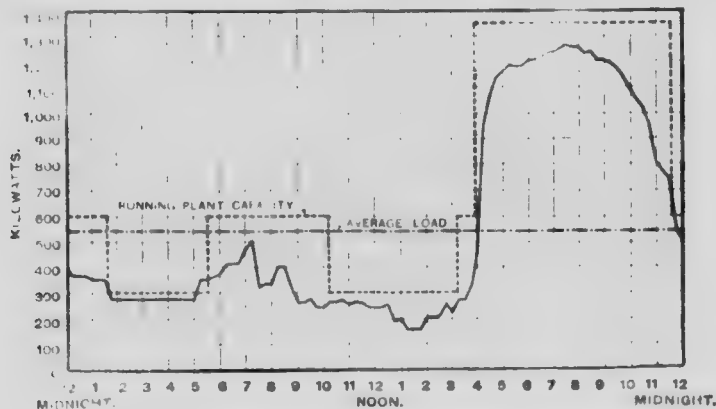


Fig. 436. Load Diagram showing Capacity of Plant Actually Running.

when an additional 300 kilowatts was started up and run till a little after 10 a.m. At 10 a.m. the load allowed the running plant to be reduced to 100 kilowatts, at which it remained for over five hours, until 3.15 p.m., when an additional 300 kilowatt unit had to be brought into action, to be followed by the bringing in at 4 p.m. of a further 750 kilowatts, making 1,350 kilowatts in all. The whole 1,350 kilowatts was kept fairly well employed until 11.30 p.m., when it was reduced to 600 kilowatts, lasting until midnight, after which the cycle would start over again.

Two other facts emerge from the diagram. First, the space between the dotted line and the curve represents the idle power of the plant running, which is not being utilised at the time, or, to put it in other words, the under-loading of the running plant. Secondly, there is drawn horizontally on the diagram a chain-dotted line which is the average load line, and which shows the output of the plant which would have supplied the whole of the daily load had that load been constant throughout the whole of the twenty-four hours.

This is seen to be about 540 kilowatts, so that for about fifteen hours extra plant had to be installed and run over and above that which would have supplied the total energy demanded if only this energy had been taken at a uniform rate throughout. This extra plant, rendered necessary by the irregularity of the load, is a measure of the increase caused thereby in the capital charge for running plant, and incidentally for buildings.

Referring back to Fig. 435, with these considerations in view, it would

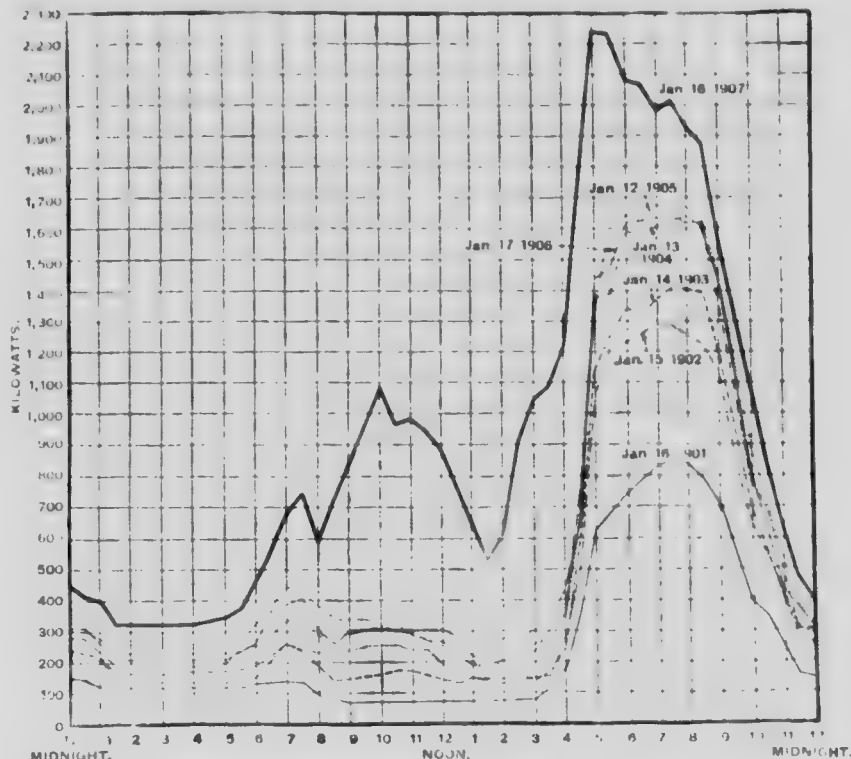


Fig. 437.—Combined Power and Lighting Load Curve in London

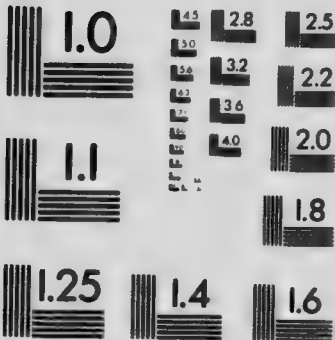
be obvious that the load curve in that figure is very disadvantageous to the economical working of the station, inasmuch as such a curve necessitates the lying idle of a great amount of plant during the greater part of the twenty-four hours. Moreover, the curve was for a mid-January day, when the hours of lighting are heavier than at midsummer, and therefore represents one of the most favourable days for the particular conditions of the station.

The ideal load is indicated by the horizontal line of the average load shown in Fig. 436. This ideal will be the more nearly approximated to the more level the load curve of the station becomes.



MICROCOPY RESOLUTION TEST CHART

(ANSI and ISO TEST CHART No. 2)



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It is obvious, then, that what is required from this point of view is to obtain a heavy day load, and that this would be most favourable to the station if it could be taken off when the hours of darkness intervene and the peak of the lighting load is coming on. The curves in Fig. 437, taken from the same station as Fig. 435, show this very clearly. The station is situated at West Ham, in the East End of London, and the curve given in Fig. 435 is the lowest curve on this diagram. The curves above it are drawn at intervals of about one year apart, and show the progressive change in the character of the load due to the cultivation of customers requiring power during the day. The final thick line curve, dated January 10th, 1907, is very instructive from this point of view. But, first, it may

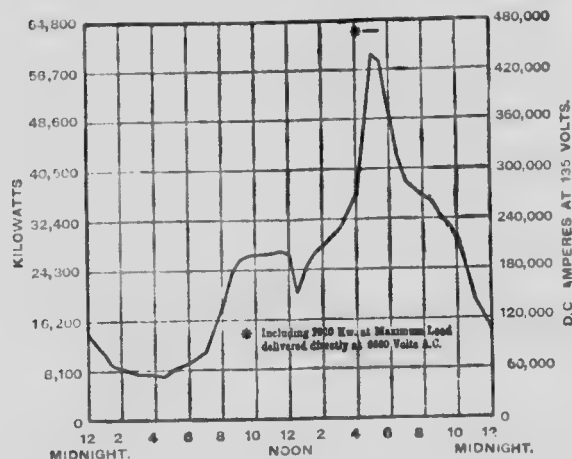


Fig. 433.—Combined Power and Lighting Load Curve in New York.

be noted that the bad character of the curve in Fig. 435 is not entirely due to the district, but rather to the fact that in 1901 the power load had not been cultivated and developed. Examining in detail the thick line curve, it will be noticed that after a low interval between 1.30 a.m. and 5.30 a.m., there is a rise up to 7.30 a.m., and that then there is a slight dip, probably due to the shutting down of some motors on account of the breakfast hour at the factories. After this the day load rises steadily until 10 a.m., and continues fairly steady until 12 noon, when there is a fall until about 2.30 p.m., due to the intervention of dinner hours, the greatest dip occurring at 1.30 p.m., after which the morning load is rapidly recovered, to be followed by the peak load which occurs at 5 p.m. and is caused by the lighting. The somewhat rapid fall between 5 p.m. and 7 p.m. is probably due to the taking off of a large part of the motor load. After 8 o'clock, due, first of all to the closing of the shops, and later on to the diminution of domestic requirements, the curve very rapidly drops until midnight.

It is interesting to compare this curve for an industrial and residential district in London with a similar midwinter curve for the Edison waterside station in New York. The American curve is given in Fig. 438, and bears a general resemblance to the London curve of Fig. 437. It is, however, much smoother, because the total amount of power being handled is very

much greater. The chief difference is in the characteristic of the peak load, which in New York is very sharp at about 5 in the afternoon and falls rapidly at 7 o'clock, showing that the power and lighting loads were only on for this short time simultaneously, from which it may be deduced that the greater part of the load up to 4 o'clock is a power load, and after 6.30 a lighting load. The existence of such a sharp peak is very much against economical capital charges at the generating station.

The general character of a factory load is shown in Fig. 439, which is the day load curve for a textile mill in Yorkshire. The curve only extends from 6.30 a.m. to 6 p.m. At 6.30 a.m. the full load comes on quite quickly, and lasts until breakfast time, a little after 8 a.m. With an interval of half an hour only the day load comes on again until the dinner hour, which appears to be between 12.30 p.m. and 1.30 p.m., after which the afternoon load comes on, and with but slight variation continues steady until 6 p.m., when the load is taken off entirely. The jagged appearance of the curve is due, of course, to the starting and stopping of separate machines. It will be readily understood that this curve superimposed upon the curve of Fig. 435, would very much improve the load diagram of that figure if the ordinates of the superimposed curve were only high enough.

So far we have been dealing with curves showing midwinter or nearly midwinter loads, but from what has been said it is obvious that these curves will be subject to seasonal variations so far as they are affected by the load being partly required for lighting purposes.

The difference between a midwinter and a midsummer series of curves is very well given in Figs. 440 and 441, which show, for successive years, the midwinter and midsummer load diagrams of the electric supply station of Poplar, a district in the middle of the East End of London. Incidentally the curves show the development of the station in successive years; but, confining our attention to the topmost curves in each diagram, the point we are interested in at the moment is the dip in the midsummer curve due to the absence of the lighting load which is present in the midwinter curve. The midsummer curve, in fact, looks very like the curve of the textile mill (Fig. 439), between 6 a.m. and 6 p.m., with the exception that the rise of the load after the breakfast hour and the closing down in the afternoon is more gradual. A good deal of the power having been taken off by 6 p.m., the next peak, not a very high one, occurs at 9 p.m., when artificial light is required in London, even in midsummer. After 9 p.m. the demands for light diminish, but remain fairly heavy until 2.30 a.m., an indication of social conditions.

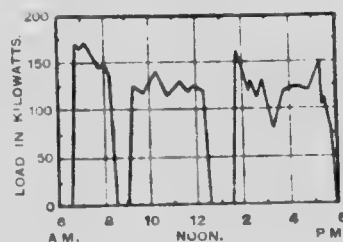


Fig. 439.--Typical Load Curve of a Factory.

A similar difference in the load curves for midwinter and midsummer at the City Road Station, planted in an industrial district in the middle of London, is shown in Fig. 442, which the reader will find interesting if studied in detail. An earlier dinner-hour is clearly indicated in the mid-

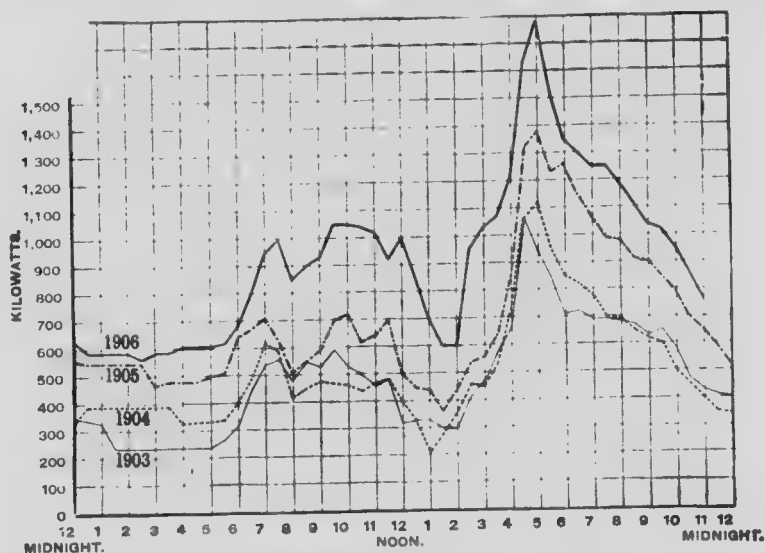


Fig. 440.—Successive Midwinter Load Curves in Poplar (London).

summer curve, and likewise the comparative lightness of the afternoon factory load.

Even the days of the week, as might be expected, have their influence

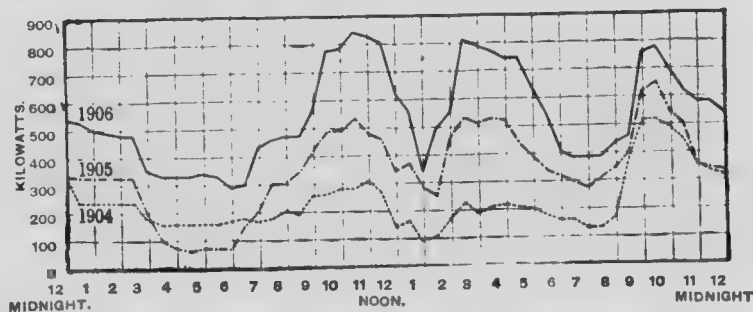


Fig. 441.—Successive Midsummer Load Curves in Poplar (London).

on the load curves. Passing over Sundays, which, obviously, in England, will have special load curves, according to the locality, the differences between Saturdays and mid-week days is strikingly shown in Fig. 443, in which the two thick-line curves give the loads on the Wandsworth (London) Station on

a Saturday in December and June respectively. The two thin-line curves, on the other hand, give two corresponding curves for Wednesdays. Both in December and June the influence of late shopping and the Saturday evening amusements and pleasuring in keeping up the load on the station, as well as in raising the maximum load, is very marked. Incidentally, the seasonal variation between midwinter and midsummer is also shown by these curves.

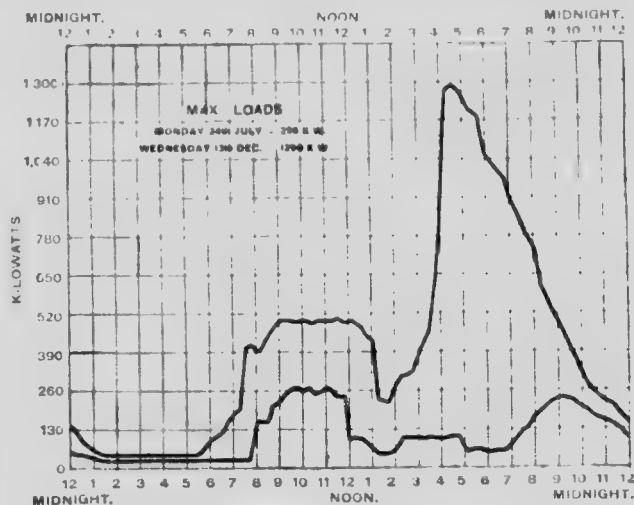


Fig. 442.—Midwinter and Midsummer Load Curves in Central London.

The seasonal variation is shown more in detail in Fig. 443, which is plotted from the weekly output in kilowatt hours of the Bow station of

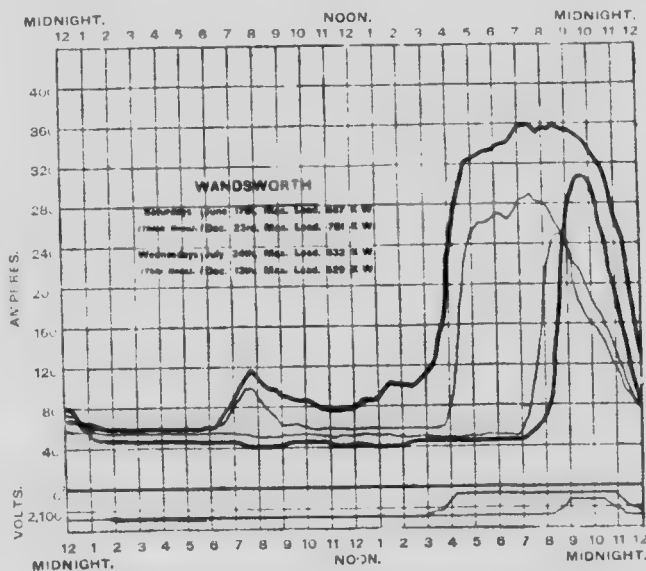


Fig. 443.—Saturday and Wednesday Load Curves, Wandsworth (London).

the Charing Cross Company. This station, although itself in the East-end of London, serves a large district in the city and further west in the metropolis. The load curve is the one drawn with the full line, and practically explains itself. With variations from week to week there is a rapid fall in the load from mid-

February to mid-April, after which the load falls more gradually until July, and then begins to rise again as the hours of daylight shorten, returning to the full winter load about the third week in November. The curve

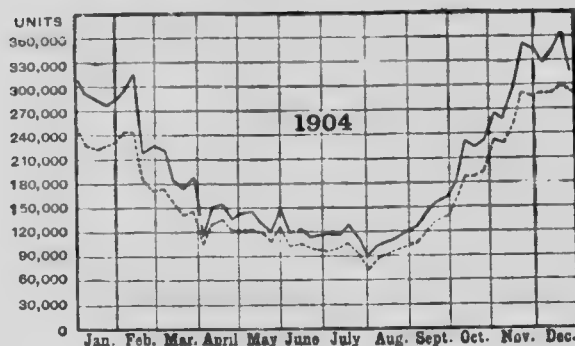


Fig. 444.—Annual Load Curve in London.

ends in December a little higher than it started in January, the difference being due to permanent additions to the load during the year. The dotted curve is also of interest, for it shows the weekly coal consumption, plotted to the kilowatt scale at the rate of 4 lb. of coal to the kilowatt

hour. It shows how closely the coal consumption follows the load, as, indeed, would otherwise have been expected; and it is also interesting as showing that throughout the year the consumption is less than 4 lb. of coal per kilowatt-hour.

The same influence of the seasons is shown in still greater detail in Fig. 445, in which there are twelve load diagrams giving the mean daily curve for each month of the year 1903. The curves are taken from the Neptune Bank Power station of the Newcastle-upon-Tyne Power Company, and will well repay careful study. An analysis of the curves shows that 80 per cent. of the energy supplied was supplied at, or below, the normal or average

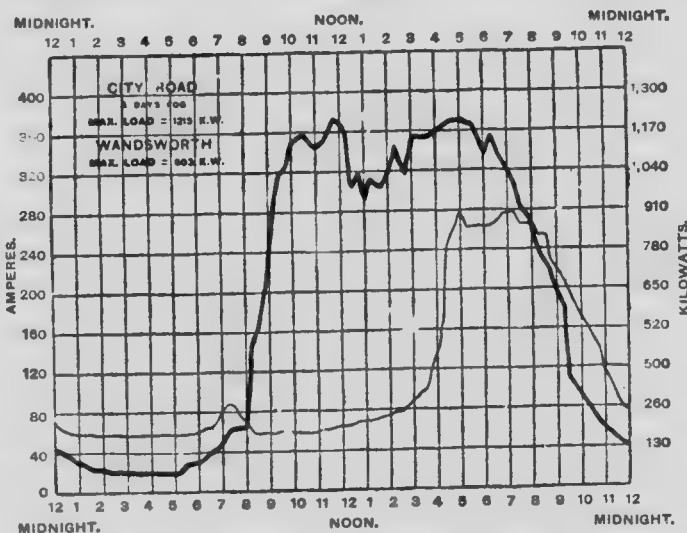


Fig. 446.—Influence of Fog in November in London.

load on the station, and that only 20 per cent. was supplied above this average load up to the peak load, which was about double the average.

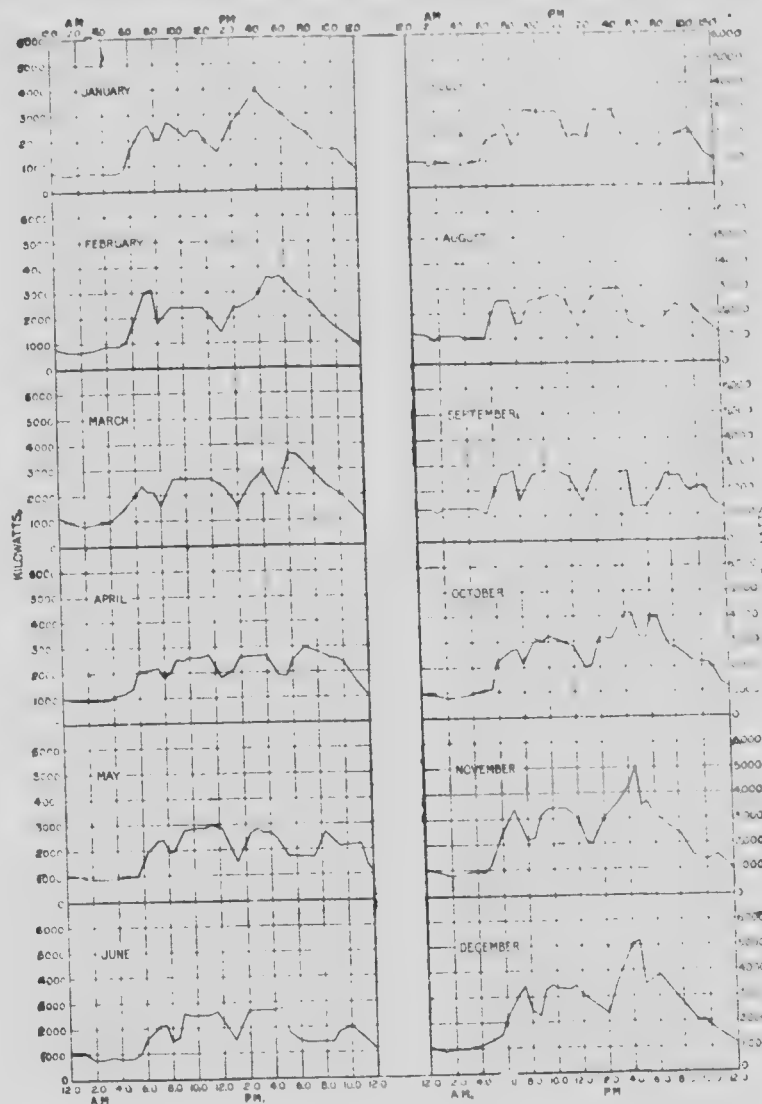


Fig. 445.—Load Curves on Typical Day for Each Month in 1903, Neptune Bank Power Station.

It is further obvious that climatic influences from day to day will also affect the load curve; but, in addition to the risk of being tedious by over-

elaborating so many points, space will not allow us to go into much detail. In these islands, and especially in London, the particular climatic influence which may suddenly and without any warning throw an unexpected and heavy load on the station, is a dense fog occurring during the daytime. In Fig. 446, will be found a very striking instance of two load curves taken on the same days in different parts of London, in one of which there was a dense fog and in the other fairly bright sunshine, although the date was the 30th November.

The use of such load diagrams will now be apparent in connection with our general subject. When planning a new station, it is desirable that hypothetical diagrams, based upon the social and industrial conditions prevailing in the district, should be drawn, and from these the best arrangement of plant, especially as regards the size of the units to be installed, should be deduced. The diagram should also give some indication of the provision to be made for dealing with the peak loads, either by the installation of additional machinery or by the use of storage batteries or otherwise.

Load Factors.—The effect of the load diagram upon the working of the station is usually summed up in what is known as the "Load Factor," which may be defined thus:—

$$\text{Load Factor} = \frac{\text{units generated per year}}{\text{maximum load} \times \text{hours per year (8,760)}}$$

The higher the load factor the more favourable is the average load diagram of the year to the economical working of the station. The factor obviously depends upon the ratio of the average load taken throughout the year to the maximum load demanded at any particular time, and this depends very largely upon the way in which, and the times at which, the different consumers require their electric energy.

Diversity Factors.—As bearing upon this question, it is now considered desirable to take account also of what is known as the "Diversity Factor," a factor which embodies an attempt to put into figures the influence of the diverse demands of the consumers, both in time and in quantity of power required. It is defined thus:—

$$\text{Diversity Factor} = \frac{\text{sum of the maximum loads of all the consumers}}{\text{maximum load on the station}}$$

The effect of the diversity of the demand upon the final load curve is very well shown in Fig. 447, which is taken from the Thornhill power station of the Yorkshire Electric Power Company's system. The power of different classes of consumers is shown in the various curves at the lower part of the diagram, the load at the station being shown by the thick line curve at the top. The various sections of power are: (a) a colliery load for coal cutting, etc., shown by the fine, dotted curve. This load practically ceases after 2 o'clock in the afternoon, though a small supply is taken between 4 p.m. and 7 p.m. In addition to this, there is (b) a lighting load

shown by the heavy dotted curve; this has the usual character, to which reference has already been made, including a high peak between 4 p.m. and 7 p.m. The next type of load is (c) the mill load, the characteristics of which have been already dealt with in Fig. 439, and which is shown again in Fig. 447 by the fine-line continuous curve. Finally there is (d) a colliery pumping load which is perfectly steady throughout the twenty-four hours, except that it is taken off entirely between 4 p.m. and 7 p.m., the time of the high peak of the lighting load. The result of these four types of load is that the final curve of the station is an extremely favourable one—much more favourable than would be given by any of the individual curves, with the exception of the pumping load, which is absolutely steady whilst the pumps are in operation.

To sum up this section of the subject, reference may be made to the results obtained in 1909 by Mr. H. M. Hobart, who by an elaborate analysis of the statistics available from a number of typical towns in Great Britain and on the Continent of Europe, arrived at the following estimate of the probable annual demand for electric energy in a hypothetical town of 1,000,000 inhabitants:—

	Kilowatt hours	
For interior electric lighting	11,700,000	
For street lighting	2,900,000	
For surface electric tramways	16,000,000	
For electric railways	43,000,000	
For electric power	3,500,000	
Total	77,100,000	

He further pointed out that, in view of the previous rate of development, it would be reasonable to expect an increase of 50 per cent. in the

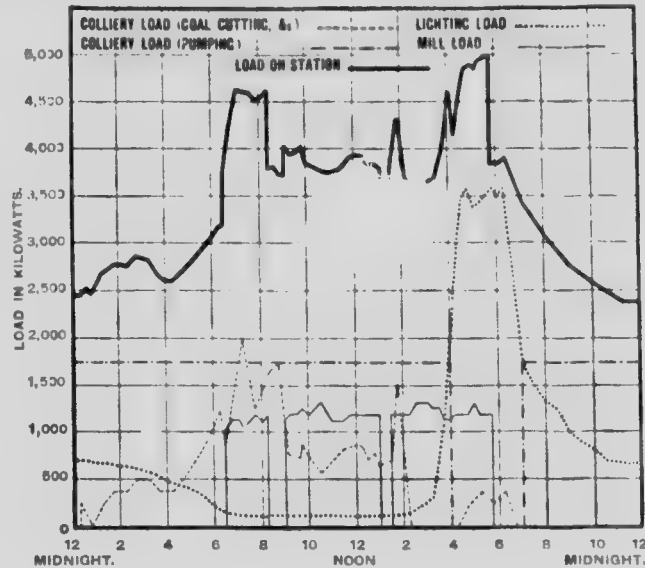


Fig. 447.—Influence of Diversity of Demand on the Load Curve.

annual demand during the next ten years. The figures given are based on averages, and are for towns only, but they are very interesting as showing the general trend for the cases dealt with. As already pointed out,

however, each individual case must be dealt with on its merits in deciding the size of station to be erected initially, and the provision to be made for extensions.

An interesting commentary on the calculations and predictions of Mr. Hobart is given by a comparison of the load curves for the Deptford generating station of the London Electric Supply Corporation and the Grosvenor Gallery Generating station, its predecessor twenty-four years earlier. The two curves are given in Fig. 448, and the increase has been so great in the interval of nearly a quarter of a century that the details of the small curve are not very clear on the small scale upon which it has to be drawn. It is not, of course, suggested that this comparison provides any data for present-day calculations; the interest is purely historical. It may, however,

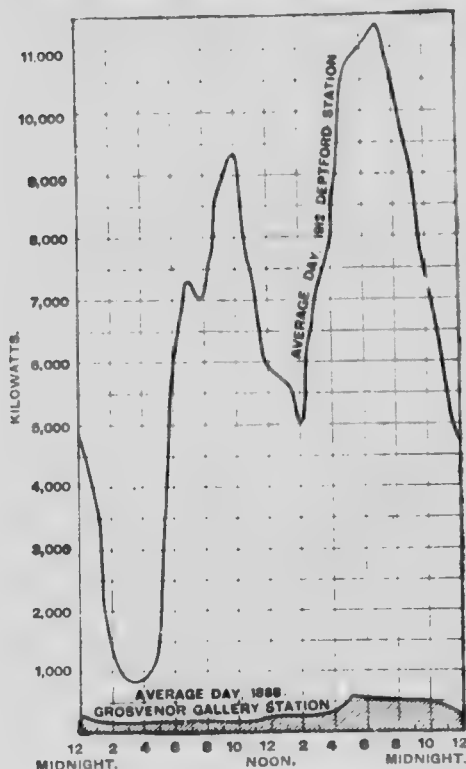


Fig. 448.—London Load Curves, 24 Years Apart (1888-1912).

be pointed out that the later curve is a typical London curve for a West-end residential and club district.

IV. (i).—STEAM-DRIVEN STATIONS

These constitute the great majority of the stations erected up to the present time, the second place being taken by the hydro-electric stations, and the gas- or oil-driven stations, coming a long way behind. Whether the present rapid development of internal combustion engines, including the well-known Diesel engine, will, in due course, seriously affect the proportion of the three types, remains to be seen. The advantages and disadvantages of each type will be referred to, each in its proper place.

In steam-driven stations, the main operations can be briefly summed

up, and are matters of common knowledge. The source of the energy used is fuel* in the form of coal, or, to a minor extent, mineral oil, wood, peat or other fuel. The first transformation is to convert the energy of the fuel into the energy of heat, as stored in steam, by means of steam-raising plant; the second is to convert the energy of the steam into mechanical energy by means of steam-engines, whether reciprocating or rotary, and the final transformation is the conversion of the mechanical energy into electrical energy by means of so-called electric generators. This book is chiefly concerned with the last of these transformations, and the design and construction of the generators have been very fully treated in the two preceding chapters. The other two transformations are equally important, and their treatment in as full detail would require a similar amount of space. Although, however, the problems and the principles involved are full of interest, and at times fascinating, the interest and the fascination are of a kind different from that aroused by our main object. We must, for details, therefore, if only because of considerations of space, refer our readers to special treatises on steam-raising plant and steam engines, and confine ourselves in what follows to such broad outlines of the main problems and their solution as may seem desirable to a clear understanding of the subject.

At each end of the chain of transformations there lies a problem, each of which must have its influence upon the important question of the location, as distinct from the particular site, of the station. Before we can start our transformations, we must obtain a supply of fuel, and when the transformations are accomplished, we must utilise in the service of man the electrical energy we have obtained. The facilities for such utilisation and the possibilities of their future development are the controlling factors in determining the size of the station, and the provision to be made for extensions.

At the other end of the chain there is the problem of fuel supply in dealing with which, not only the general location, but also the peculiarities of the particular site must be carefully considered. It is absolutely essential that the fuel should be delivered with the least possible expenditure for carriage, and in this connection it is well to remember that water carriage is, as a rule, much cheaper than land carriage. The arrangements for handling the fuel economically when it has reached the station are, of course, part of the plan of the station, but they partly depend upon the method by which the fuel is brought to the station, and the two problems should be considered together.

As influencing the choice of the site of the station it is obvious that a

* It is of course always to be borne in mind that fuel by itself is not a source of energy, for it would be useless without a practically unlimited supply of the oxygen of the atmosphere. To avoid circumlocution, however, it is usual to omit all reference to the necessary air except when making calculations and arrangements for its supply to the combustion chambers.

good supply of water is necessary for the production of steam, even though the same water be used over and over again by being passed back to the boilers through the condensers. It must also be remembered that modern steam plant works most economically with good condensers capable of producing a high vacuum, and that for this purpose a large quantity of cheap cooling water is absolutely essential. Cases have occurred in which facilities for obtaining cheap cooling water have been the final factor in determining the actual site for the station.

Plan of Station.—The site of the station having been selected, the next principal matter to be determined is its division between the different sections necessary for the carrying on of the work. The main sections are: (i.) the steam-raising plant, for which a boiler-house and its accessories will be required, and (ii.) the engine and generator room, which usually includes (iii.) the switch gallery and its accessory chambers, though the switching arrangements in some of the most recent stations are in a separate building. Administrative offices and repairing shops may also have to be provided.

The greater part of the area will be required for (i.) and (ii.), and the proportion to be assigned to each is important. This proportion depends upon several considerations. Besides the loss of energy involved in the treble transformation referred to above, one of the great disadvantages of a steam-driven station is the large amount of space required for the steam-raising plant and the condensing plant. Recent developments which have reduced the space necessary for the engines and generators required for a given output, have accentuated this disadvantage.

This change in the relative ground space required by the two largest sections of the station is strikingly illustrated in Fig. 449, which gives the ground plans of two stations, built successively by the New York Edison Company, on the East River, in New York City, and known respectively as "Waterside Station" and "Waterside Station, No. 2." The first of these was opened with its initial equipment, having a full-load capacity of 32,000 kilowatts, late in 1901, having probably been designed some eighteen months earlier. Extensions were contemplated, which would bring the capacity of the station up to 64,000 kilowatts, which, at the time of its projection, was considered to be sufficient for the demands likely to arise for many years. Within three years of the opening, however, it had become evident that the provision was not nearly sufficient, and that a station of still larger capacity was required in addition. In the interval, short as it was, there had taken place a rapid development in the production of steam turbines, so that the large reciprocating engine sets which the original station was designed to accommodate, had, in the opinion of the responsible engineers, been, to a great extent, superseded. But it will be evident from many of the particulars given in the preceding chapter that a turbo-

generator set, including the engine, occupies much less space than a slow-speed set, whether C. C. or A. C., of equal output, a point which will be further elaborated presently. Consequently, the new station was

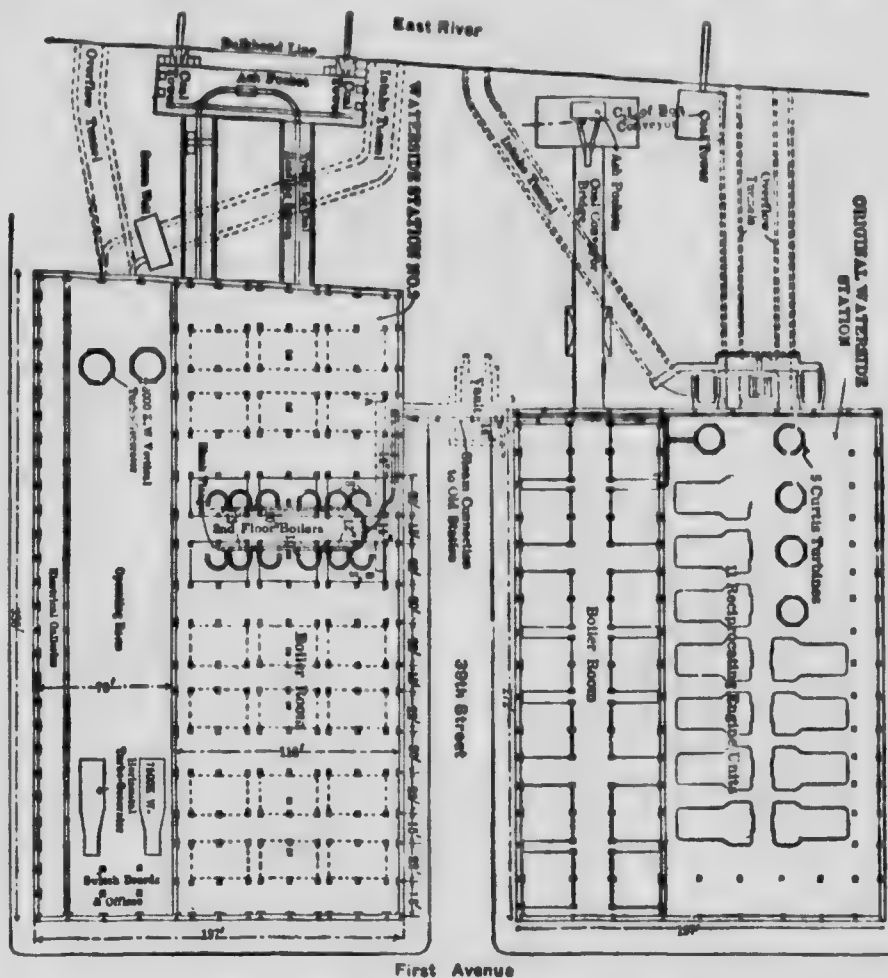


Fig. 449.—Plan of Two Successive Stations in New York City.

designed with the relative boiler and engine-room spaces required by the new conditions, and a glance at the two plans is sufficient to emphasise the change.

If we examine the plans more closely, we find that the ground space occupied by the two boiler rooms is 19,700 and 39,900 square feet respec-

tively. In calculating the ground space in the two engine rooms, the side electrical galleries should be excluded in both cases, these having set against them the space required outside the building for accessories connected with the steam-raising plant. With these allowances, the engine-

room areas are 27,400 and 18,590 square feet in the original and in No. 2 station respectively. The ratio of engine-room space to boiler-room space is, therefore, as 100 to 72 in the original station, but has fallen to 100 to 214 in No. 2 Station; in other words, in the later station the boilers occupy relatively

three times the ground space. It is further interesting and important to note that the

two buildings cover an over-all ground space of 53,500 and 66,500 square feet respectively. The rated full-load output of the earlier station was 72,000 kilowatts, and of the later station is 80,000 kilowatts. The comparison, however, should be between the overload capacities, which were 90,000 kilowatts for the earlier station, and 120,000 kilowatts for the more recent one. As boilers cannot be overloaded 50 per cent. like turbo-alternators, if advantage is to

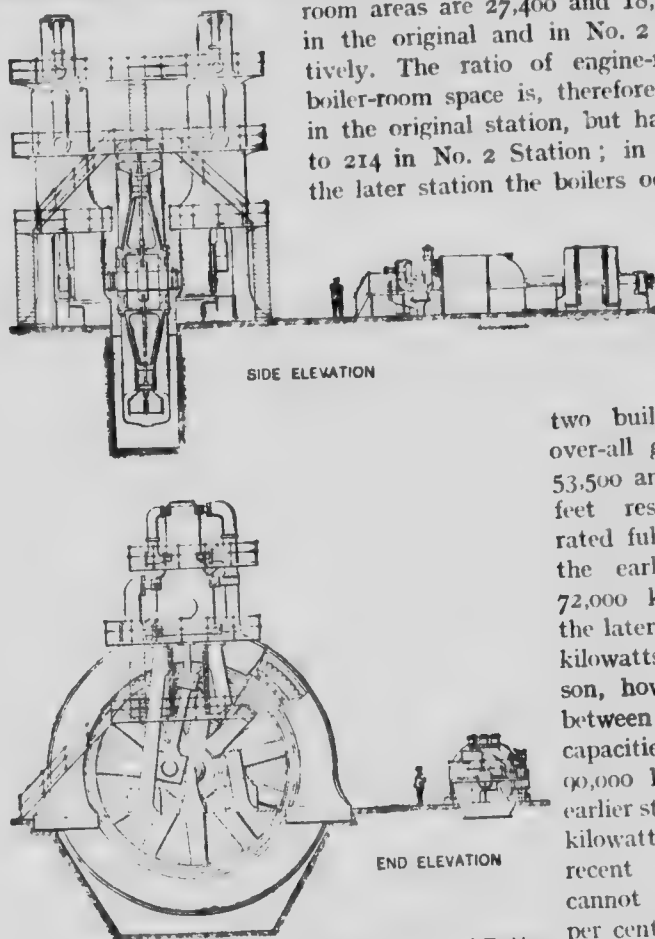


Fig. 450.—Comparison of Reciprocating Engine Sets and Turbine Sets of the Same Output.

be taken of the overload capacity of the generators, the necessary extra boiler capacity must be available. Hence, the boiler space in the No. 2 Station is on a more liberal scale than in the original station. As, however, the ground space occupied by the boiler room is nearly doubled in the later station, it would appear to be capable of carrying a heavier load than that stated above, a supposition which is confirmed by noticing that the

engine room can probably accommodate either more or larger units. In comparing the actual boiler space in these stations with the similar space in some of those subsequently described, it should be noted that the boilers in the Waterside stations are on two floors, one over the other, thus diminishing the amount of ground area to be covered for a given steam-raising capacity, as compared with a station in which all the boilers are on the same level.

Before leaving Fig. 449, it is interesting to note that even before the original station was fully equipped, the development of turbo-alternators had proceeded so far that the last five units to be installed were turbine units in lieu of slow-speed reciprocating engine units.

The contrast between the space occupied by modern turbo-generators and the reciprocating engine sets which preceded them is shown very strikingly in Fig. 450, which gives, side by side, the end elevation of two steam generating sets of 10,000 H. P. each, as installed in the Deptford generating station of the London Supply Corporation. The large set was built in 1889, and the small turbo-generator set of the same output in 1912. It is interesting to note in passing that the 1889 set was the first electric generating set to be constructed of so large a size as 10,000 H. P. A further feature of

interest is that in the same station, a little earlier, had been laid down for the first time large generating machines generating electric alternate current energy at the high pressure of 10,000 volts.

This contrast between reciprocating sets and turbo-alternators is shown still more graphically in Fig. 451. The set shown in dark tone is a turbo-alternator set standing on its foundations and of the same output as the large reciprocating set shown in light tone, also standing on its foundations. The illustration not only emphasises the difference in cubical dimensions between the two sets themselves, but also shows the much larger and more expensive foundations which are required for the reciprocating set—foundations which substantially increase the capital cost. It will be readily understood as has already been pointed out that this difference in size of modern generating plant and of reciprocating plant, which is as yet by no means ancient, profoundly



Fig. 451.—Turbo-Alternator compared with a Reciprocating Set.

affects the relative amount of space required in the engine rooms and the boiler rooms of generating stations.

Plans and some details of the plant in a few typical stations will now be given, the switching and controlling arrangements being reserved for a subsequent section.

London County Council Station, Greenwich.—The diagrams given in Fig. 452 are the ground plan and longitudinal and cross sections of the Greenwich generating station of the London County Council tramways, as designed about the year 1903. At that date the recent develop-

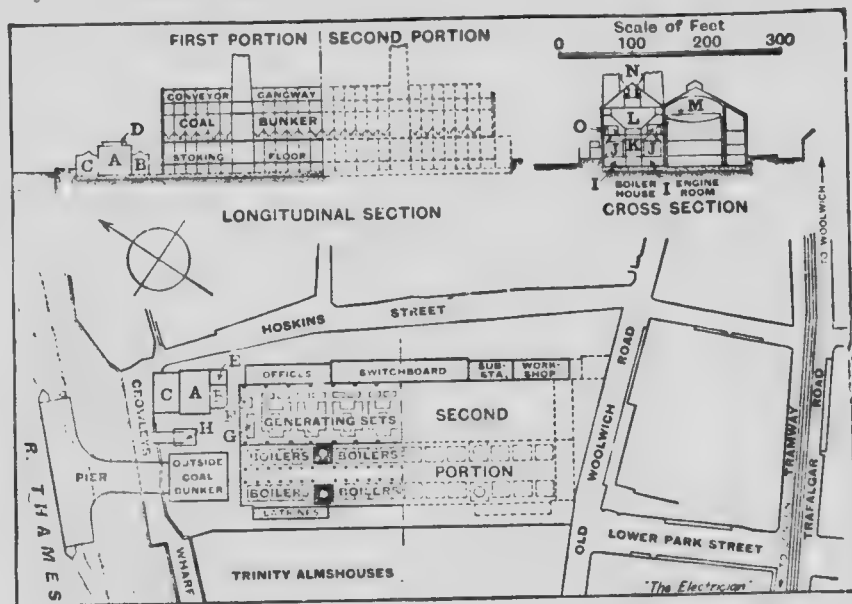


Fig. 452.—Original Ground Plan and Sections of the Greenwich Power Station for the London County Council Tramways.

ment of turbo-generators had not taken place, and the station was designed for reciprocating engines. The plan, therefore, shows the most up-to-date arrangement of that period for such engines. The station is situated on the banks of the river Thames at Greenwich, and a special pier enables it to obtain its coal supply by water carriage direct to the coal bunker, shown at the left of the plan. The boiler house and engine room are placed side by side, and provision was made for them to be extended simultaneously as necessity required. The auxiliary plant, including the pumps, coal bunkers, etc., is all collected at one end of the station so that the boilers and their corresponding generating sets are not interfered with by it. The longitudinal and cross sections at the top of the figure give some further general details. The scale of feet given in the

figure shows that the main building was to be about 400 feet long and about 225 feet wide. The station was originally designed and equipped with boiler plant for an output of 34,000 kilowatts. The chimneys, four in number, are placed two and two in the centre of each half of the boiler house, and it is interesting, in passing, to note that these chimneys are practically on the first meridian, and when subsequently they began to discharge their heated gases into the atmosphere they disturbed the meridian observations

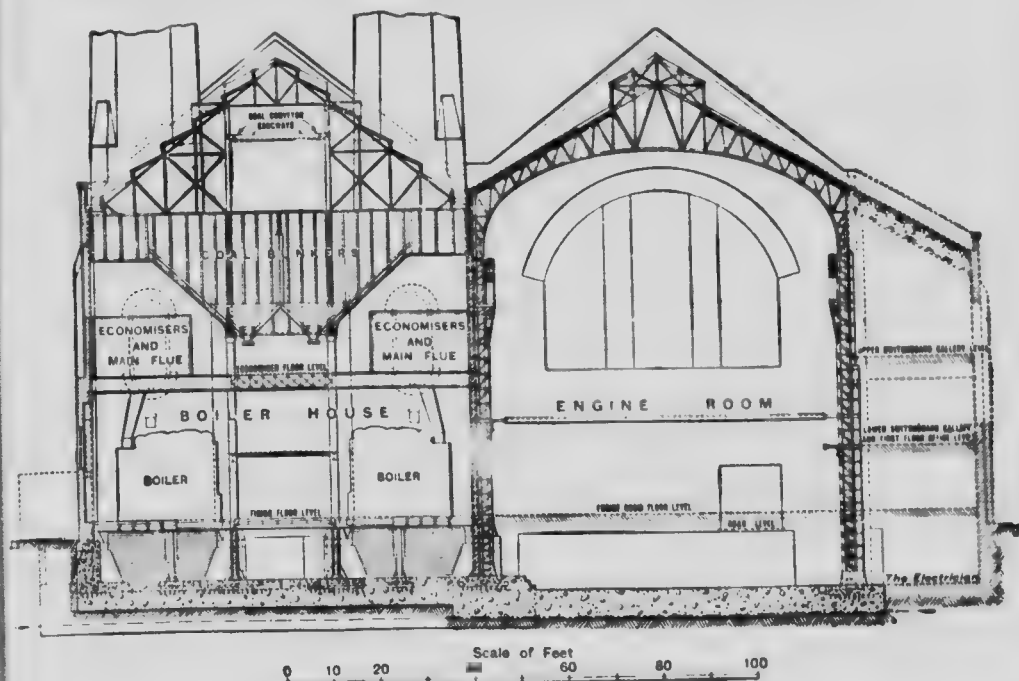


Fig. 453.—Cross-Section of the London Tramways Power House.

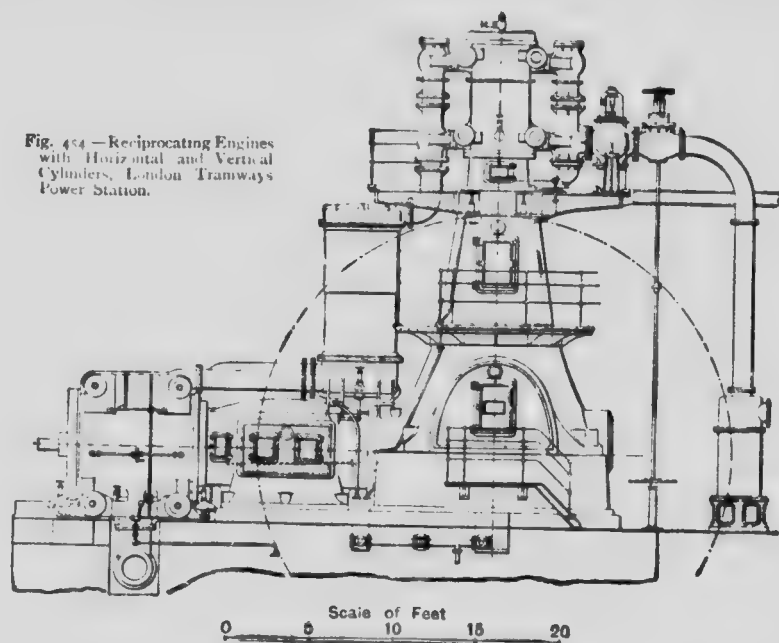
of the Greenwich Observatory, particularly the observations of the transit circle from which Greenwich mean time is calculated.

As regards the relative space for boiler house and engine room, the width is very nearly the same, the boiler room being a little the larger; but the cubical space enclosed by the latter is very much more fully occupied, as will be evident from an inspection of Fig. 453, which shows on a large scale a cross-section of the station through the boiler house, engine room, and switch and apparatus galleries. The boilers are in two ranges on either side of a central gangway, the main flue and the economisers being on a higher level leading to the base of the chimneys, which are 250 feet high. Each boiler can evaporate from 15,000 to

16,500 lbs. of steam per hour, at a working pressure of 180 lb. per square inch. The ample size of the auxiliary coal bunker above the boilers and the space provided for coal-conveying plant may also be noted in the diagram. The switch and apparatus galleries run alongside the wall of the engine room remote from the boilers.

As already remarked, the station was planned as a reciprocating-engine station, and is being referred to as an example of such a station. The type of engine originally installed is shown in Fig. 454. Each generating

Fig. 454 — Reciprocating Engines with Horizontal and Vertical Cylinders, London Tramways Power Station.



set was made up of two such engines driving on to the same shaft, and with the alternator between them. Each engine had a high-pressure vertical cylinder and a low-pressure horizontal cylinder with their connecting rods driving on to the same crank pin. Each complete set was to develop 3,500 kilowatts when running at 64 R. P. M., and with a steam pressure of 180 lb. per square inch, and 26-inch vacuum, the steam being superheated to 500° F. The general appearance of these sets, of which there were eight in all, is shown in Fig. 455.

It is a sign of the rapid development which is taking place that since the above description was first printed an announcement has been made that four of the reciprocating engines sets described are to be forthwith changed for turbine sets. The details of the proposed changes are interesting.

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Fig. 435.—4500-Kilowatt Reciprocating Engine Sets in the Greenwich Power House.

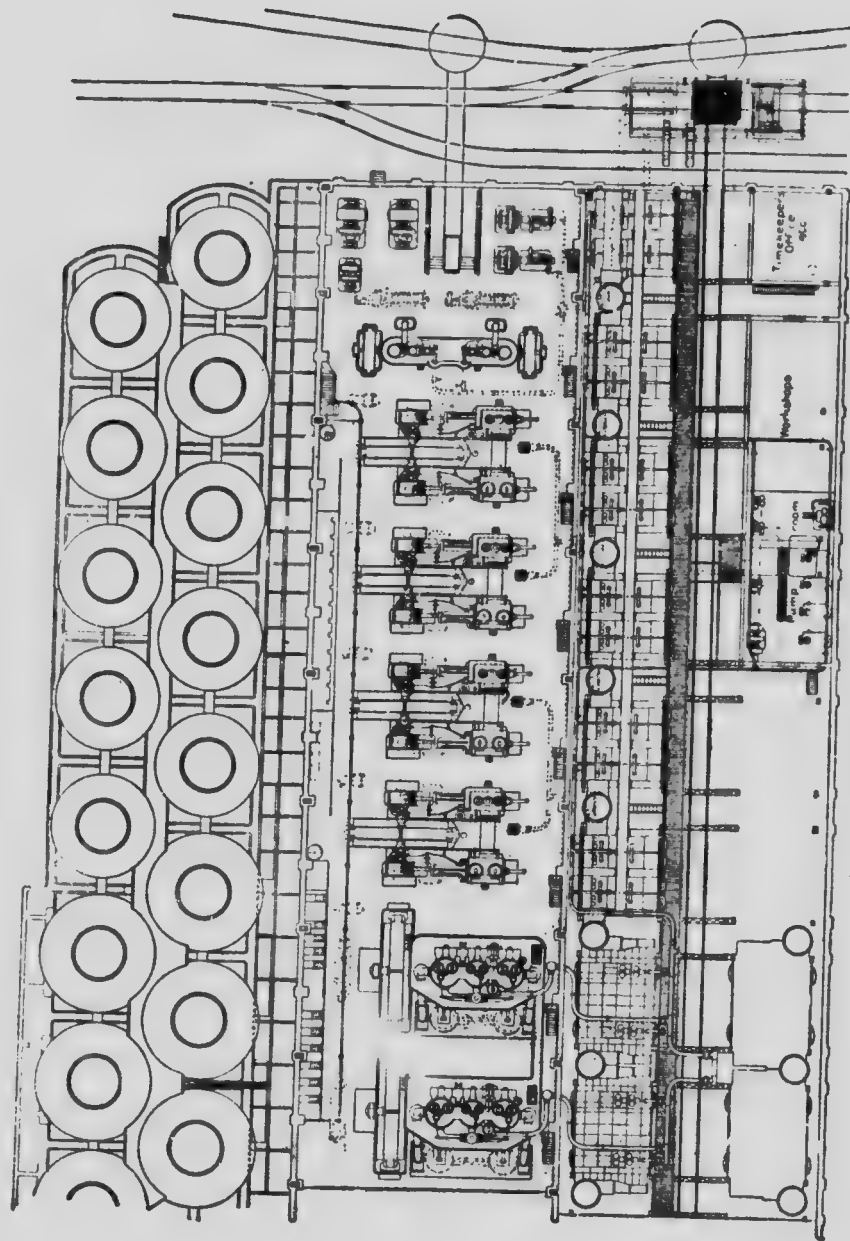


Fig. 456.—Plan of the Bow (L-aden) Generating Station (1905).

Each of the four 3,500-kilowatt sets, consisting of the coupled reciprocating engines just described and an alternator, is to be replaced by an 8,000-kilowatt turbo-alternator, thus increasing the capacity of the station by

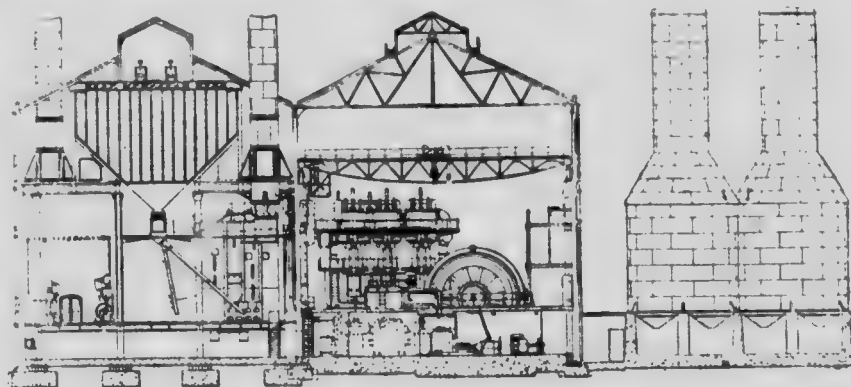


Fig. 457.—Cross-Section of Bow Generating Station.

18,000 kilowatts, or from 34,000 kilowatts to 52,000 kilowatts. The reciprocating sets originally cost £119,000, whilst the cost of the new sets, together with the cost of installing them and of some necessary consequent changes, will be £227,000.

The justification for so costly a change apart from the increase in the capacity of the station and other things, lies in the saving in fuel which, with coal at 11s. per ton, is estimated at £11,430 for the first two turbine sets to be installed, a sum which represents a handsome percentage on the cost of the sets without allowing for the selling value of the old plant.

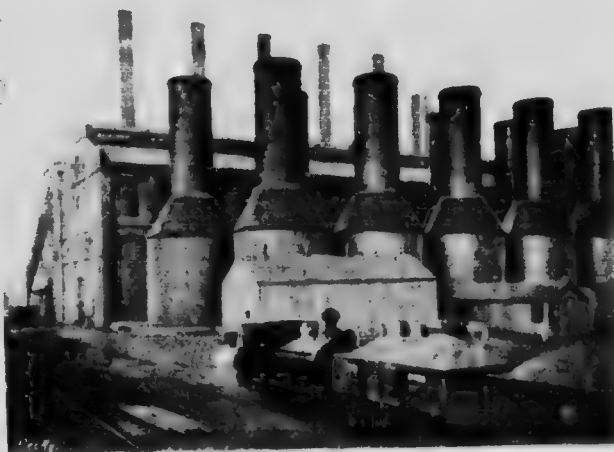


Fig. 458.—View of Bow Generating Station.

Notwithstanding these pending changes the above description of the original Greenwich power station may be allowed to remain, and will

repay careful study as a description of a well-planned modern reciprocating-engine station.



Fig. 459.—Interior of Bow Generating Station (1907).

Bow Generating Station.—As another example of a station designed for reciprocating engines, Fig. 456 shows the plan of the Bow (London)

generating station of the Charing Cross and City Company. It was designed by Mr. W. H. Patchell about 1904, the plan given being published in 1905. A cross-section is shown in Fig. 457, from which it will be seen that in this instance the width of the engine room, which, however, includes the space required for the switchboards, is equal to that of the boiler room. As shown in the sectional elevation the boilers were, as at Greenwich, in two rows on either side of a central gangway, and were to be supplied with coal from a bunker in the roof. In the

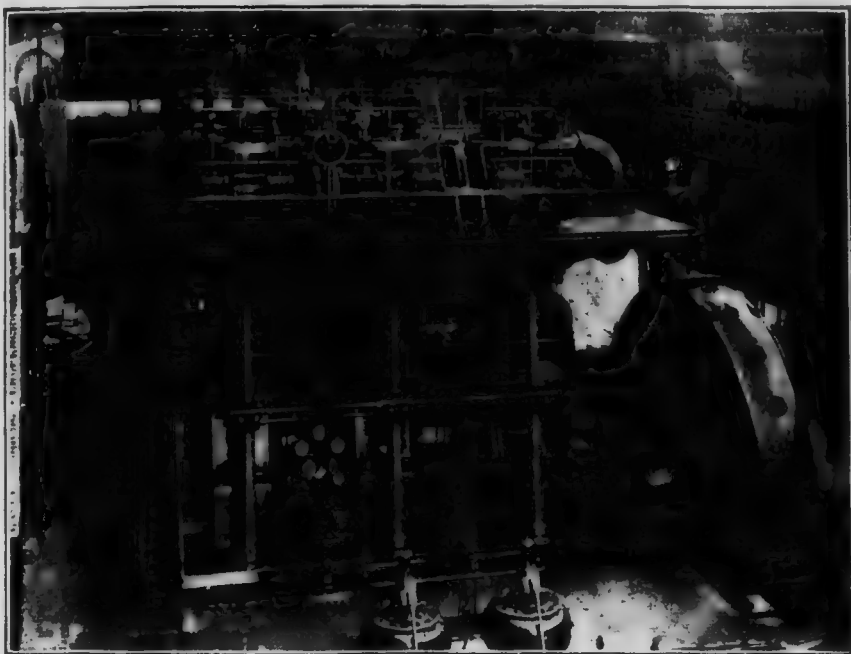


Fig. 460.—Vertical 4,000-h.p. Reciprocating-Engine Set in Bow Generating Station.

plan (Fig. 456) the double row of boilers is only shown at the left hand end, for at that end the reciprocating sets were vertical, and each of 6,000-H. P. output at 83.3 R. P. M. In the other part of the engine room there are shown in the plan four horizontal sets of smaller size, developing nominally 2,500 B. H. P. at 83.3 R. P. M. A view of the station as seen from the outside is given in Fig. 458, and both in this view and the plan of Fig. 456 the cooling towers are very prominent. These cooling towers are 85 feet high to the top of the chimneys and 30 feet in diameter in their lowest parts.

The engine room, as it appeared in 1907, is shown in Fig. 459, in which the horizontal engines are in the foreground and the high-speed vertical sets

at the far end. The latter sets are more clearly seen in Fig. 460, in which it will be noted that there are three cylinders driving a three-throw crank shaft, on one end of which the alternator is fixed. The centre cylinder is the high-pressure cylinder, 50½ inches in diameter, and on each side of it there is a low-pressure cylinder 70¾ inches in diameter. The power developed by these engines at 83½ R. P. M. is, as already mentioned, 6,000 H.P.

The output of the alternator is 4,000 kilowatts. The four horizontal engines and generators, developing 1,600 kilowatts each at 83½ R. P. M., are shown separately in Fig. 461. The steam pressure for the above outputs was 170 lb. per square inch, with 70° F. of superheat, and the vacuum was 26 inches.

Bradford Station.—The generators referred to in the two stations

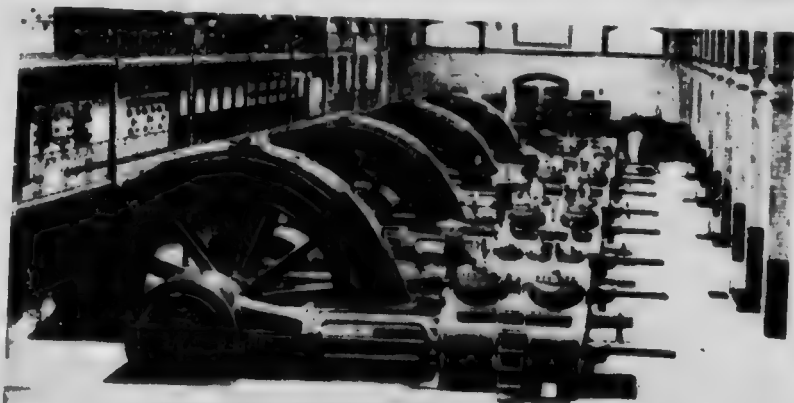


Fig. 461.—Horizontal 1,600 K. W. Reciprocating Engine Sets in Bow Generating Station.

described above are slow-speed generators. As an example of a station using, in addition, generating sets with high-speed reciprocating engines, Fig. 462 shows the ground plan of the generating station of the city of Bradford, in which are also turbo-generators. More strictly speaking, the station consists of two stations, marked in the plan as "No. 2" and "No. 3," each with its own boiler house and engine room, the former being the station to be first erected. This being so, one is not surprised to find that the relative arrangement of boiler house and engine room in No. 2 station differs from that in No. 3, which is of the more modern type, with the boilers near to the sets to which they are to give steam. In No. 2, the older, engine room there are twelve Willans high-speed vertical engines. The steam piping is now arranged so that these sets can receive steam from No. 3 boiler house, the boilers in No. 2 boiler house only being used during the periods of the year when the load is heavy.

Station No. 3 is a further interesting example of the economy of space so far as the engine room is concerned, obtained by using turbo-alternators. It was originally designed for five reciprocating engine sets, each having an output of 1,000 kilowatts at 85 R. P. M., and the plan of the room

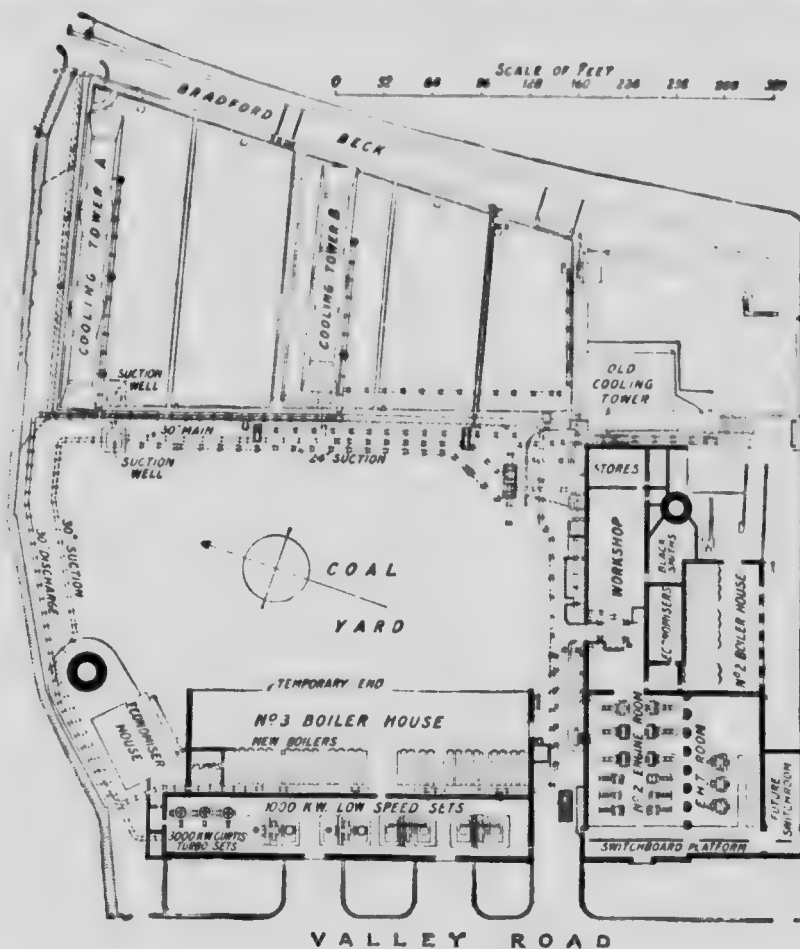


Fig. 462.—Plan of Bradford Generating Station.

given in Fig. 462 shows four of these sets installed, and having, therefore, altogether an output of 4,000 kilowatts. The space for the fifth set, however, has been utilised to install three Curtis vertical turbine sets, each of 3,000-kilowatts output, but with an overload capacity of 50 per cent., and therefore capable of taking a total load of 13,500 kilowatts.

The following additional comparative figures are both interesting and instructive:—

	<i>Turbo-Alternator</i>	<i>Low-speed Set</i>
Output in kilowatts	4,500	1,000
Speed (R. P. M.)	1,500	85
Floor space occupied (sq. ft.)	57	683
Diameter of largest rotating portion	76 in.	240 in.
Weight of rotating parts	15 tons	103 tons
Weight of plant	60 tons	193 tons
Weight of steam used per hour	72,000 lb.	20,000 lb.
Weight of steam per kw.-hr. generated	16 lb.	20 lb.

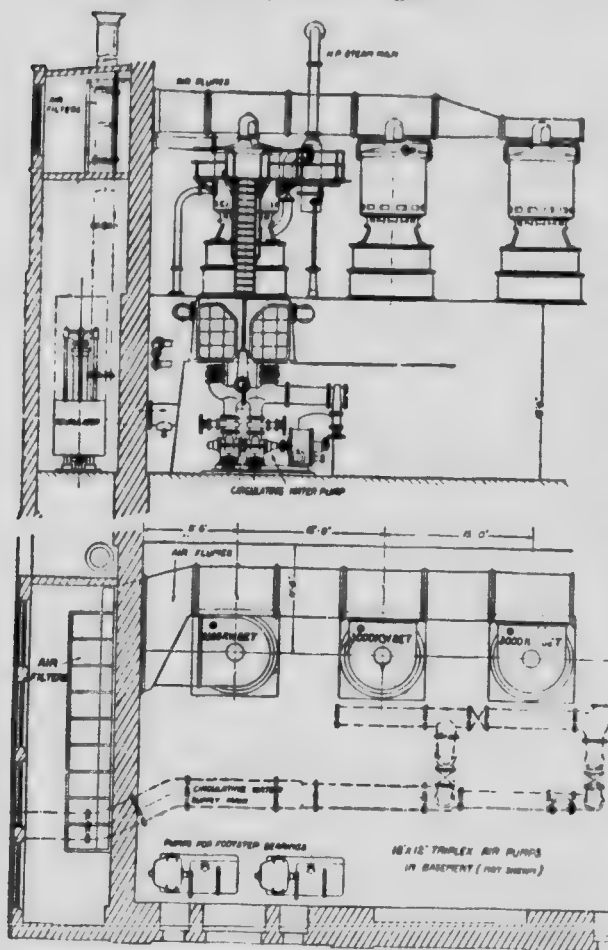


Fig. 463.—Arrangement of Curtis Turbo-Alternators at Bradford.

Some details of the arrangement of these sets are given in Fig. 463, which gives a diagrammatic plan and elevation of the three turbine sets with some of the principal dimensions added. Much of the economy of space in the engine room is obtained by placing the condensing plant in a basement 18 feet high. There is an ample supply of cool air obtained through the air flumes from the air filters at the side. These sets as they appear in the engine room are shown in Fig. 464; they stand about 18 feet high, measured from the floor of the engine room.

Carville Power Station.—As an example of a modern turbo-alternator

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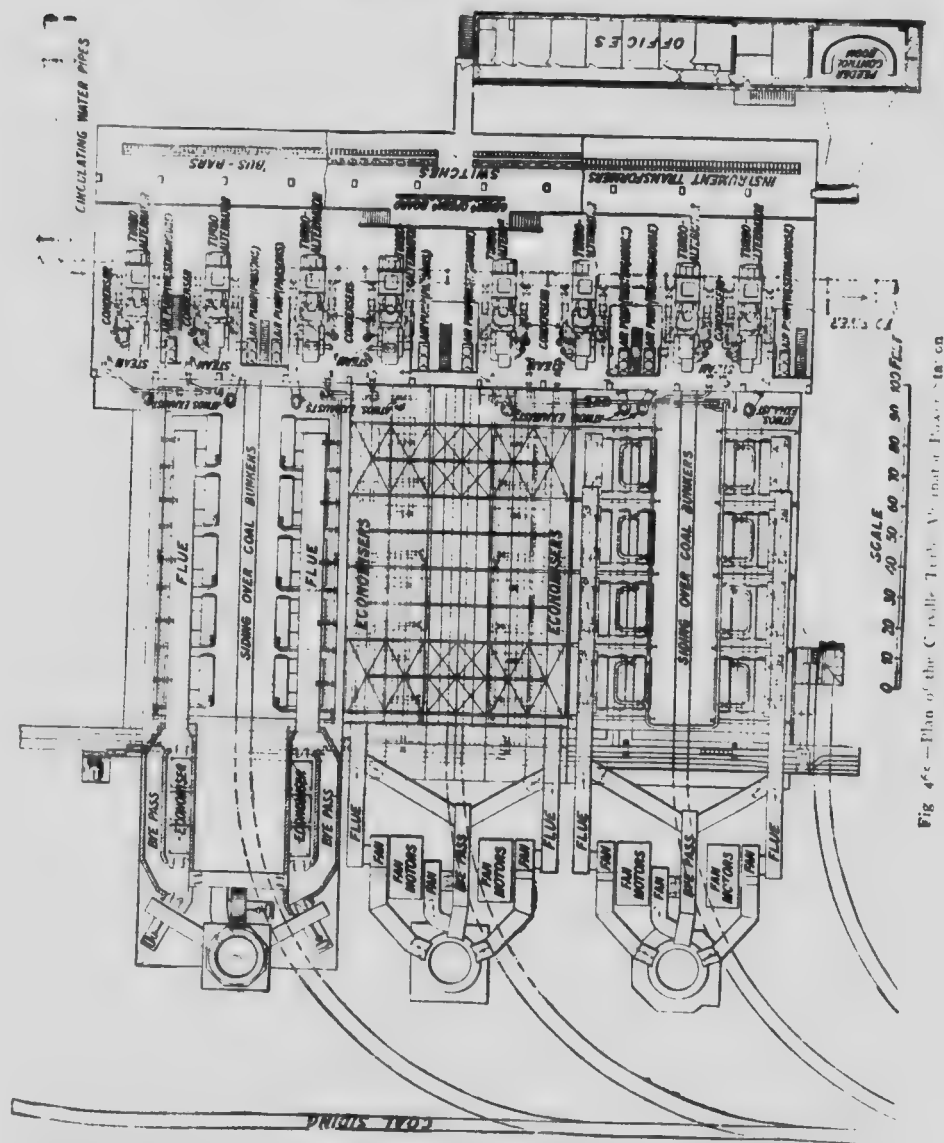
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Fig. 474. Curtis Vertical Shaft Turbine in the 1400-hp Generating Station.

station, Fig. 465 gives ground plan, and Fig. 466 gives a sectional elevation of the Carville power station of the Newcastle-upon-Tyne Electric



made for their extension *pari passu*, the boiler houses, with their chimneys and accessories, occupy a very much greater superficial area than the engine room occupies. There are shown in the diagram (Fig. 465) three boiler houses alongside one another, and each of them end-on to the engine room, a scale of feet being given at the side. The total maximum capacity of the station is 52,000 H. P., divided between eight Parsons' turbo-alternator generating sets, six of which are normally rated at 5,000 kilowatts and the remaining two at 4,500 kilowatts each. The boiler house on the left of Fig. 465 contains ten Babcock and Wilcox water-tube boilers of the marine type, each having a steaming capacity of 20,000 lb. of steam per hour. The other two boiler houses each contain eight Sterling boilers, each with a steaming capacity of 25,000 lb. per hour, so that the aggregate output in steam of each boiler house is the same. An interesting feature of the station is that the coal trucks can be run from the coal siding into the bunkers above the boilers in the boiler house (see Fig. 466), an arrangement which obviously leads to economy in handling the coal. To provide for utilising the large over-load capacity of the turbo-generators it will be noticed that at the end of the boiler houses the flue gases can pass to the chimneys of each boiler house either directly or through fans driven by motors, which can create an induced draught and so increase the duty of the boilers, enabling them to raise greater quantities of steam.

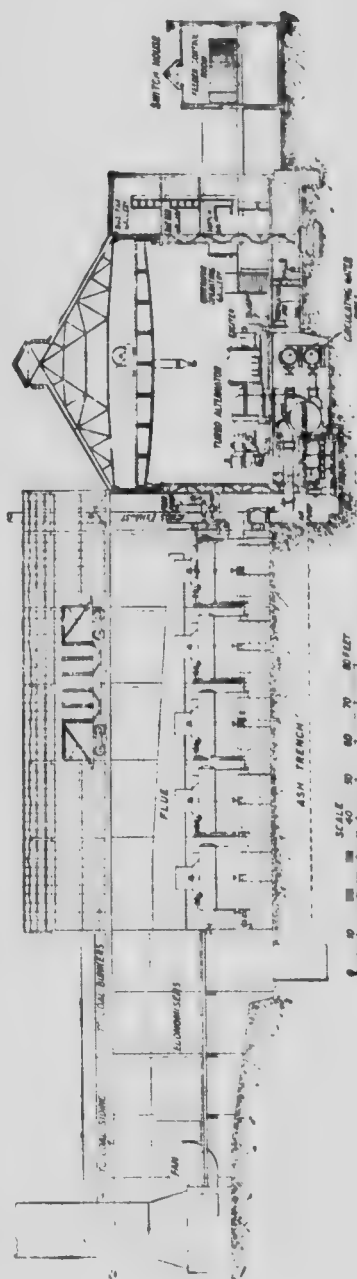


Fig. 465.—Station. Elevation of the Carville Turbo-Alternator Power Station.

Fig. 466.—Plan of the Carville Turbo-Alternator Power Station.

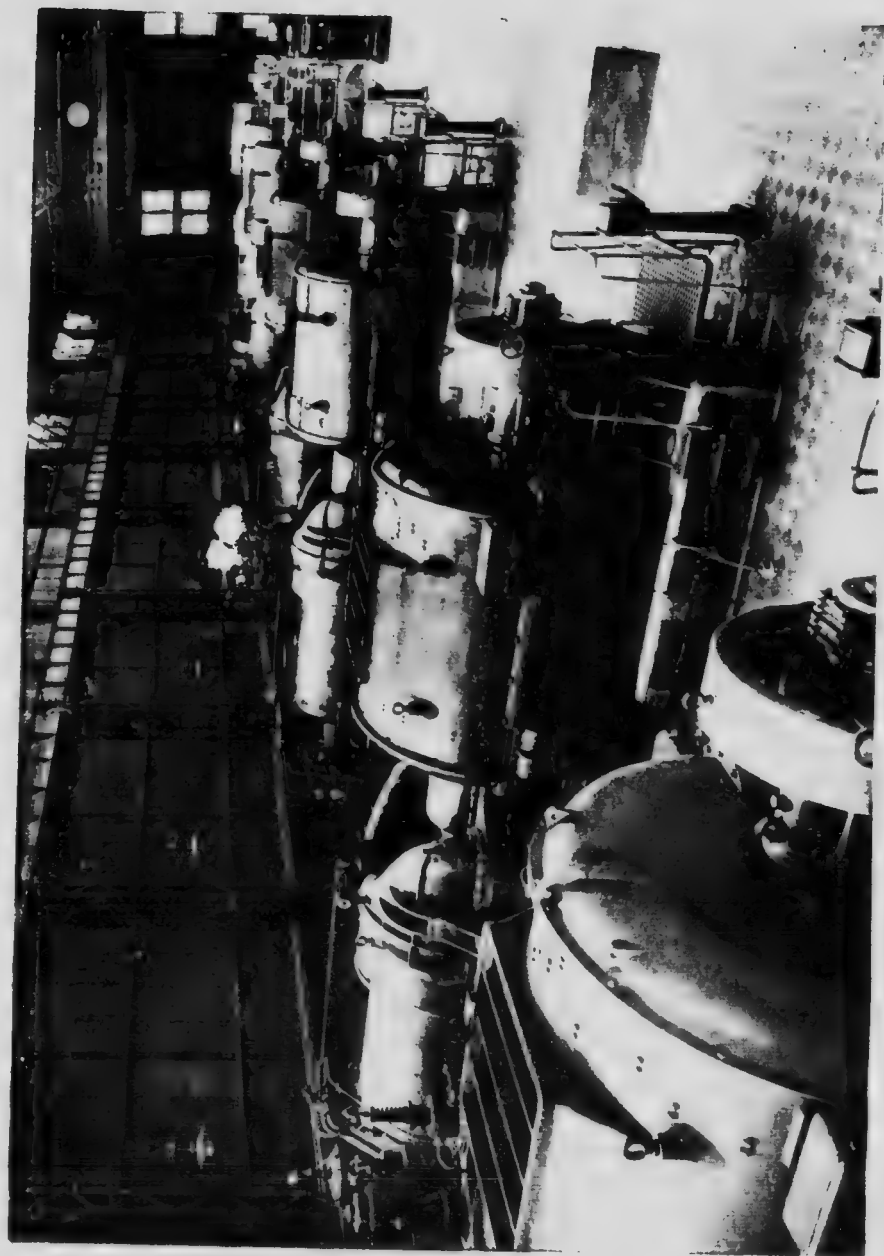


Fig. 457.—The Carville Power Station, showing Parsons Turbo-Alternator S.

A view of the engine room of the station, showing nearly all the sets, is given in Fig. 467. The illustration shows most prominently the generator ends of the various sets, with the continuous current exciters mounted on the shafts. Parsons generators have been referred to in the preceding pages (see pages 220 and 340).



Fig. 468. The Southwick Power Station of the Brighton Corporation.

Southwick Power Station.— In order to bring the steam nearer to the generating sets, power stations have been designed with the engine room in the centre and boiler rooms on either side. Such a power station is the Southwick station of the Brighton Corporation, an external view of which

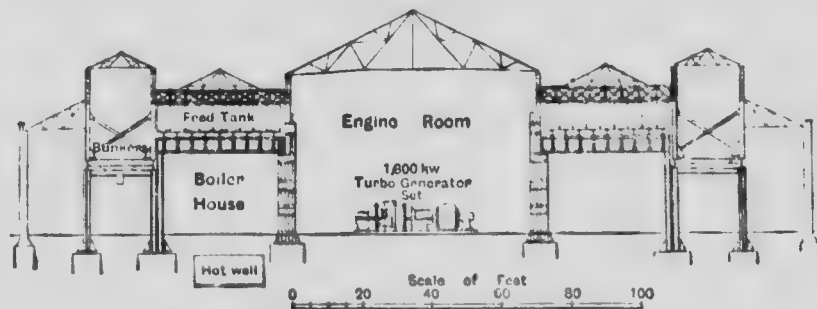


Fig. 469.—Cross-Section of the Southwick Power Station.

is given in Fig. 468. A diagrammatic cross-section of the power house, from which the general arrangement can be better deduced, is given in Fig. 469. In this instance the coal bunkers flank the boiler houses on either side and on a higher level. The ground plan, showing rather more than two-thirds of the station, including one of the boiler

houses and the engine room, is given in Fig. 470. The first part of the power station was opened in June, 1906, but additional units have been added from time to time, and gradually of larger capacity. At the beginning each unit installed had an output of 1,800 kilowatts, but subsequently this was increased to 3,500 kilowatts, with an overload capacity up to 4,000. As in previous examples, to provide for the overload capacity of the turbo-generators, plant for induced draught has been installed for use in times of heavy load. Further details can be readily made out from the plan, but in view of the previous descriptions of other stations need not be referred to here.

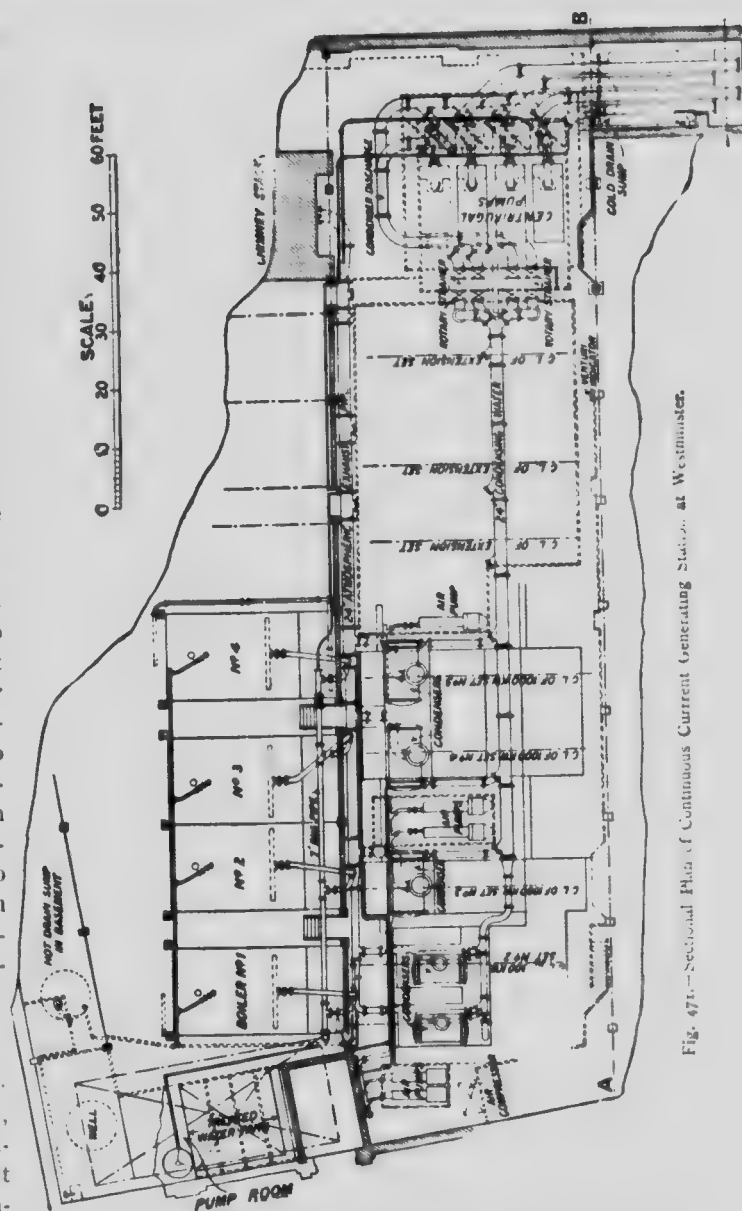


Fig. 471.—Sectional Plan of Continuous Current Generating Station at Westminster.

Westminster Station.—As a final example of a generating station, equipped with modern machinery, Fig. 471 shows the plan of a generat-

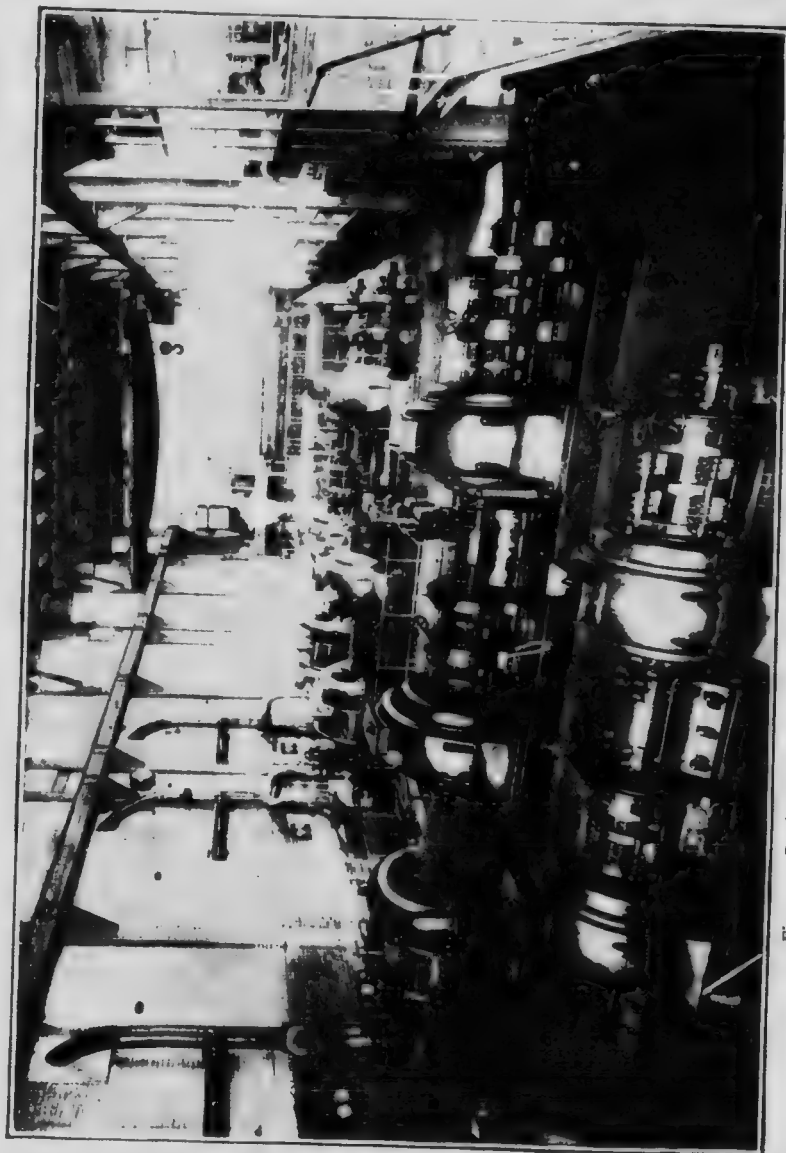


Fig. 47a.—Continuous Current Generating Station of the Westminster Supply Corporation.

ing station recently erected by the Westminster Supply Corporation. This, like the London County Council station, is situated on the banks of the

Thames, but higher up the river, in Horseferry Road, Westminster, and is of interest as being perhaps one of the very few large generating stations in which only continuous current turbo-generators are installed. The turbo-generators referred to in the preceding descriptions of generating stations were, without exception, turbo-alternators. In this case there are three 1,000-kilowatt continuous current Siemens turbo-generators, running at 1,850 R. P. M., and two 300-kilowatt continuous current steam balancer sets, running at 3,000 R. P. M. The boiler room, as in several of the previous plans, is parallel with the engine room, and is so planned that extensions of both can proceed simultaneously. The influence of the size of the generator sets on the ground space occupied by the engines and boilers respectively is again shown in this diagram, where, however, owing to the comparative smallness of the generator sets, they, with their condenser equipment, and owing to the arrangement of this equipment, occupy a greater floor space than the steam-raising plant.

A view of the engine room of this station is given in Fig. 472, in which one of the two comparatively small balancer sets appears in the foreground, the large generating sets being shown farther back. In these latter sets there are two dynamos each of 500 kilowatts capacity on the shaft of the single turbine. These dynamos have been described in the preceding pages (see pages 16 and 139). The turbines are Zoelly impulse machines, and the sets are designed to give one kilowatt-hour at full load with 17.1 lbs. of steam at 200 lb. per square inch, with 150° of superheat and 28½-inch vacuum. They can take 25 per cent. overload for half an hour, or 40 per cent. overload for three minutes.

Deptford Station.—We cannot perhaps conclude this section more appropriately than by giving (in Fig. 473) a view, as it at present appears, of the Deptford station of the London Electric Supply Corporation, to which some reference has already been made (see pages 432 and 436). The plant in this station is, in the aggregate, probably unique. It contains six copper-type Ferranti alternators erected many years ago and still giving a perfectly satisfactory service, though some of the steam plant driving them has been re-modelled so as to work compound. Some of the older steam plant is, however, still in use, a set consisting of three separate engines in tandem driving a single generator. Some low-speed engines using rope drives are also still in use. Side by side with all these are two 10,000 H. P. modern turbo-generators of the impulse reaction type, built by Messrs. C. A. Parsons and Co., with Brown, Boveri alternators and single-phase generators of not only the Ferranti type already mentioned, but also of the British Thomson-Houston type, giving a 10,000 volt current at 85 ω . Speaking generally, the station is in two sections, one giving energy for lighting purposes and the other for railway traction and power. The whole history of this station is a splendid tribute to British engineering

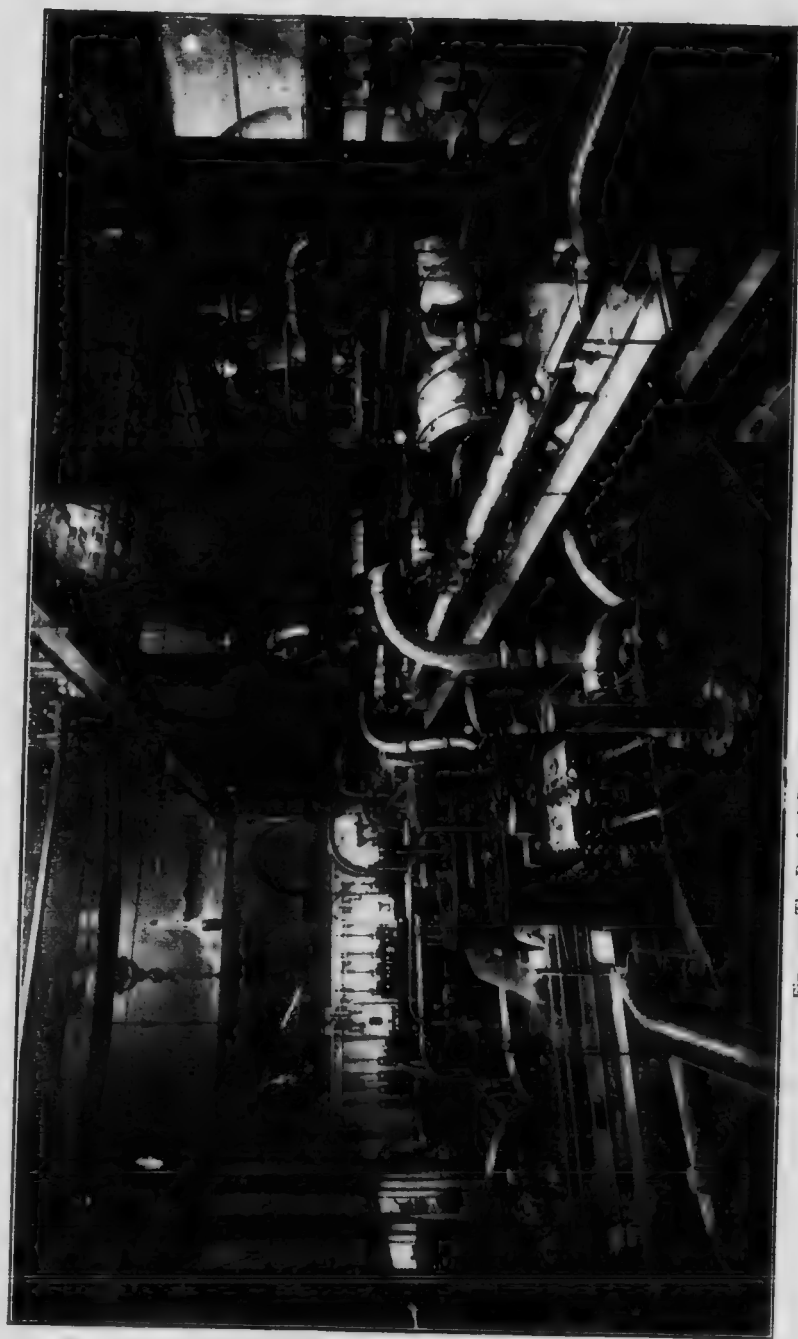


Fig. 473.—The Deptford Power Station of the London Electric Supply Corporation.

genius and enterprise on the part of Mr. Ferranti and the staff. In it many of the difficulties of handling large units and transmitting large quantities of power at high voltages were encountered and overcome for the first time in the history of the science. To-day, with all the variety of machines alluded to above, its working costs (0·82d. per unit sold) are claimed to be lower by 10 per cent. than those of any other company in London.

IV. (ii.) GAS- AND OIL-DRIVEN STATIONS

The problem of applying fuel directly to the production of power without the intervention of steam is one which has for a long period occupied the attention of engineers, and the various methods devised for this purpose have been increasingly improved during the present century. The general idea is to burn the fuel in a closed chamber in the prime mover and to utilise the expansive power of the heated products of combustion for the purpose of driving forward a piston in a cylinder. The forward movement of the piston is utilised by the intervention of a piston rod and crank to produce rotary motion, but, as in the case of steam-driven engines, the advantage of producing rotary motion directly by the action of the working fluid as in a steam turbine is obvious. The production of a satisfactory gas turbine is therefore one of the live engineering problems of the present day, and has attracted a good deal of attention.

In the earliest solutions of the general problem, gas, mixed with the proper proportion of air, was exploded somewhat violently underneath a piston attached to a vertical piston rod. Only small machines were employed, and the production of power, though of a somewhat small amount, was successfully accomplished, but with the accompanying nuisance of considerable noise and racket. The problem of causing the combustion to take place quietly has long since been solved, so that as far as the actual burning is concerned, the modern gas engine runs without excessive noise.

Before giving a general outline of the working of a modern gas- or oil-driven station, it would be well to indicate the kinds of fuel which have been found available for use in internal combustion engines generally. They may be summarised as follows:—

1. The well-known **coal gas** which is produced, for domestic and other use, at large gas works in all parts of the country, by the destructive distillation of coal in closed retorts and out of contact with air.
2. The same **coal gas enriched** by the addition of other volatile fuels, especially the hydro-carbons obtained by the distillation of petroleum, shale oil, and coal tar oils.
3. **Water gas**, obtained by decomposing super-heated steam by blowing it through incandescent anthracite coal or gas coke. The

gas so produced contains carbon monoxide and may also be enriched by the addition of hydro-carbon vapours.

4. **Producer gas**, which is made by injecting steam and air through incandescent coal. Of this gas there are two chief methods of manufacture known as the pressure method and the suction method.
5. Gas of low calorific value, which is obtained as a by-product in other industries, more especially the waste gas from the **blast furnaces** of iron smelters, and the waste gas from the **coke ovens** in which coke is made for use in foundries and blast furnaces.

It would be travelling outside the scope of this book, and would need considerably greater space than is available, if any attempt were made to describe in full detail the various processes by which the above-named

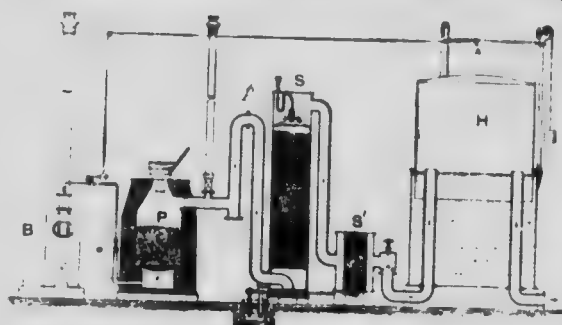


Fig. 474.—Diagram of Pressure Gas-Producer Plant.

or two actual examples may be permitted. The two kinds of producers are named in the chronological order of their development and for each kind quite a crowd of inventors is responsible for many successive improvements. It may be stated at once that, although the general idea is simple and easy to follow, besides being of great interest, the working out of the idea with engineering plant on a large scale introduces numerous points of difficulty, upon many of which the last word has not yet been said.

Pressure-Gas Plant.—In Fig. 474 * there is given a diagrammatic sketch of a "Dowson" producer-gas plant for the manufacture, under pressure, of gas for power purposes from anthracite coal, coke, or charcoal. A boiler B produces a relatively small quantity of steam which is blown upwards through the incandescent fuel in the gas producer or retort P. The steam itself is dissociated at the high temperature of the fuel, and with the air which is carried through with it the products of the dissociation, hydrogen

* This and Figs. 475 and 478 have been lent by the Dowson and Mason Gas Plant Company, Limited.

and oxygen, carry away the products of the incomplete combustion of the coal in the retort of the producer. These products are mainly carbonic oxide (CO) mixed with a little hydro-carbon gas, and a greater quantity of carbonic acid which has been formed by the complete combustion of a small part of the fuel. If the producer is working properly, the oxygen of the air and also the oxygen of the water will have been used up in forming carbonic oxide and carbonic acid. The hydrogen of the water, however, passes on as fuel with the carbonic oxide which forms the other active constituent of the mixture. The inert nitrogen of the air, which is simultaneously carried through the retort, of course passes on also, though its presence could be dispensed with if it could easily be got rid of. From the producer retort *p* the gas passes through the upright siphon-shaped pipe *q*, which acts as a cooler, to the bottom of a vertical tower *s*, known as the "scrubber," the function of which is to cool and purify the gas. The scrubber is a vertical steel cylinder, containing at intervals wooden trays on which rest pieces of coke 2 to 4 inches in size. There is a water-spraying arrangement at the top which distributes the down-flowing water evenly over the coke, so that the gas in passing up meets the water trickling down over the lumps of coke, the effect being that the water takes out most of the impurities which have been brought over from the producer. The gas then passes into another and smaller scrubber *s'*, known as the dry coke or sawdust scrubber, in which it passes over trays of dry sawdust, which remove the moisture caused by contact with the water of the wet scrubber, and also the remaining particles of dust which may have got through the coke scrubber. From this dry scrubber the gas passes into the gas holder *h*, where it is stored for use. Throughout the process the gas, in the various pieces of apparatus, is at a pressure slightly above that of the atmosphere, and therefore any leak in any part of the plant will lead to gas being driven into the outer air, where it may become a nuisance. Should it escape in large quantities the carbonic-oxide gas is especially dangerous, as it is very poisonous, and does not reveal its presence by any characteristic smell.

The foregoing is a mere general description of the process. In practice the success of any of the processes employed for the production and preparation of gas for power purposes depends on close attention to numerous details, some of which will be apparent in connection with the description of actual plants given later.

Suction-Gas Plant.—The other general method of producing gas for power purposes is the suction method, in which there is practically no attempt to store the gas, which is fed directly into the gas engines as it is produced. The suction of the gas engine drawing the gas into its cylinders lowers the pressure of the gas, from the producing retort onwards, below the pressure of the external atmosphere. If, therefore,

the plant be working properly, any leak in the connections can only lead to atmospheric air being forced inwards, none of the poisonous contents inside being able to leak outwards.

A diagrammatic sketch of such a plant is given in Fig. 475. In this plant steam and air, after passing through a warming-up jacket placed round the top of retort R, are drawn into the space below the incandescent fuel in the retort, and, passing upwards through this fuel, produce the same effect as in the pressure-gas plant described above. From the retort the mixed gases pass to the bottom of the coke scrubber S, into

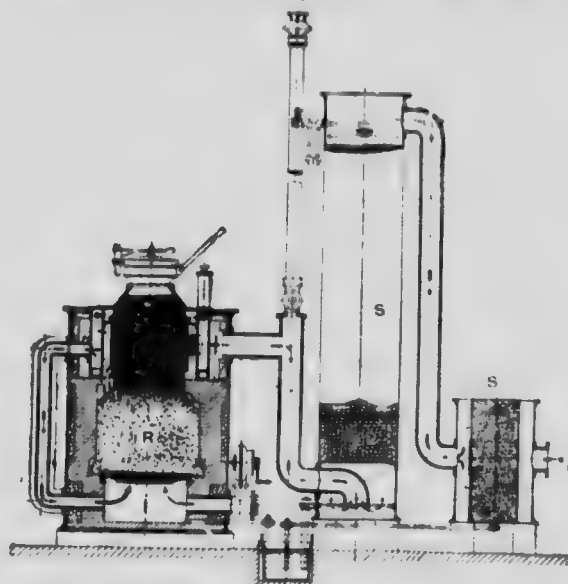


Fig. 475.—Diagram of Suction-Gas Producer Plant.

which they are discharged through a water seal. As they pass upwards through the scrubber they meet a finely divided stream of water travelling downwards over the lumps of coke or pieces of rubble with which the scrubber is loosely packed. From the top of the wet scrubber the gases are drawn through the dry scrubber S', from which, deprived of moisture, they pass direct to the gas engines.

A suction-gas plant, as designed and erected by Messrs. Crossley Bros., Limited, of Manchester, is shown in Fig. 476. It is designed to supply gas to engines having a total output of 600 B. H. P. The gases generated in the large cylindric generator on the right-hand side pass through the pipes in the "water-heater" alongside, in which they give up some of their heat to the water which is going forward to the generator, where it is converted into steam on a dish-type boiler. The gases then enter at the bottom the tall coke scrubber, from the top of which they pass to the sawdust scrubber on the extreme left, after traversing which they are ready for use in the engines. The cylindric generator is 70 ft. in over-all diameter of 96 inches, and stands 14 feet high to the top of the boiler. The whole plant stands on a floor area of about 14 feet by 32 feet, and the greatest height from the floor to the highest part of the pipe which emerges from the top of the coke

scrubber is 21 feet. This may be compared very advantageously with the space necessary for the steam-raising plant which would be required to supply the requisite steam to steam engines having an equivalent output.

Details of the construction of the sawdust scrubber shown in Fig 476

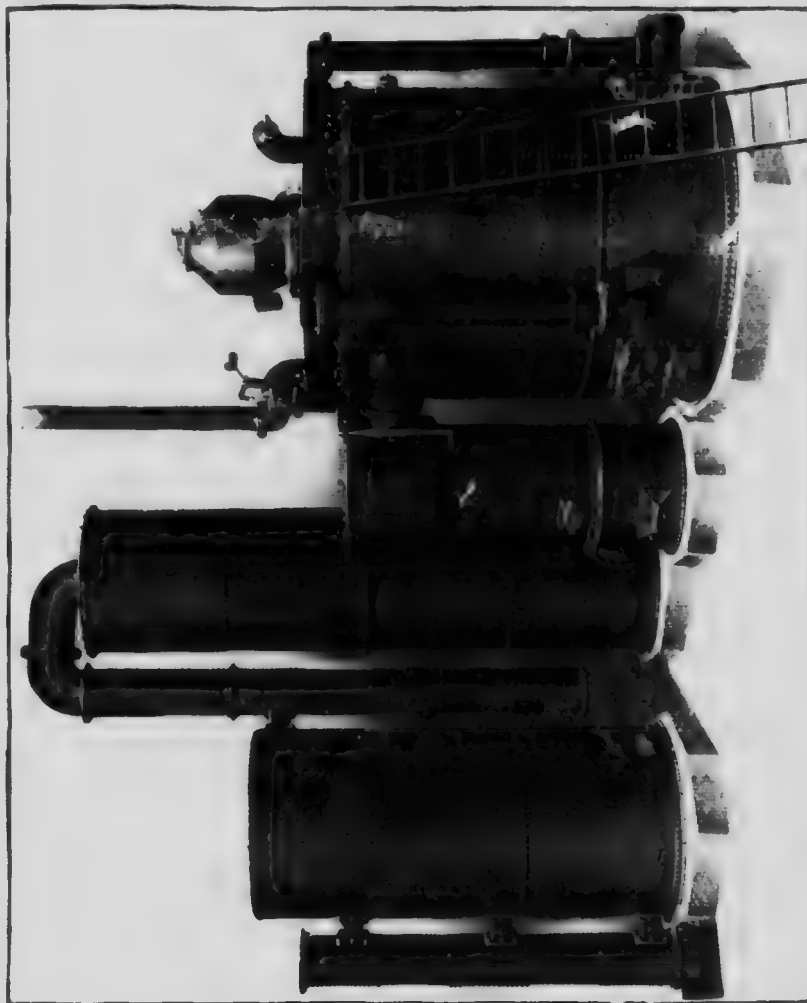


Fig. 476. Suction-Gas Producer Plant.

are given in Fig. 477. On account of the large quantity of gas to be handled the gas enters the scrubber at three different inlets, I. I. I. from the two lower of which it divides into two streams passing partly upwards and partly downwards through the layers of sawdust which are

interposed on trays between *I, I, I* and the outlets *O, O, O*. The doors for the purpose of "filling" with fresh sawdust and for "cleaning" out the scrubber and removing the sawdust which has become dirty and wet by use are clearly shown in the figure, which gives a good idea of the simplicity of the principle on which this ingenious method of removing impurities from and drying the gas is based.

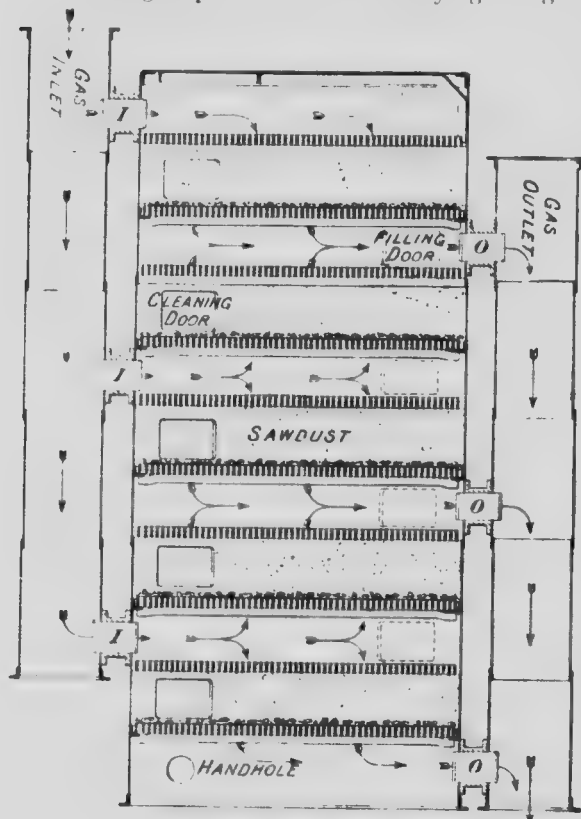


Fig. 477.—Large Crossley Sawdust Scrubber.

In its smaller plant up to 120 B. H. P., this firm places the sawdust scrubber on the top of the coke scrubber, and thus ingeniously still further reduces the necessary floor space.

One of the drawbacks of both types of plant, so far described, is that only fuel very free from bituminous constituents can be used, for with ordinary bituminous coal these bituminous constituents in the form of tar and heavy oil would be carried over, unless specially removed, into the cylinders of the gas engines, in which they would soon cause trouble by clogging up and fouling the valves, igniters, and other working parts. The

fuel, therefore, which has to be used in them must be non-bituminous, such as anthracite coal or good coke, and such fuel is very much more expensive than the ordinary fuel which is used for steam producers, the difference in price being many times greater than the difference in calorific value. This difference is an excellent illustration of the action of the economic laws of supply and demand. If, therefore, it be desired to use the bituminous and cheaper fuel, arrangements must be made to remove these troublesome constituents by special apparatus, which adds to the

complication of the plant. These constituents, however, consist of materials of commercial value, and if it be desired to recover these, the plant becomes still more complicated, and approximates more or less closely to the complete and elaborate plant of a gas works manufacturing the ordinary coal or lighting gas.

The problem of designing a suction-gas producer which can be fed with ordinary bituminous fuel has attracted a good deal of attention, and a diagram of one successful solution, as designed by the Dowson and Mason Gas Plant Company, is given in Fig. 478. The retort R, into which the bituminous coal, in lumps of suitable size, is fed, is different from that shown in Fig. 475 for anthracite coal. The coal is, as usual, fed in at the top of the retort, to which, however, the outer air has free access, and from which it is drawn downwards through the new, unburnt coal as well as upwards from the fire box through the incandescent fuel in the

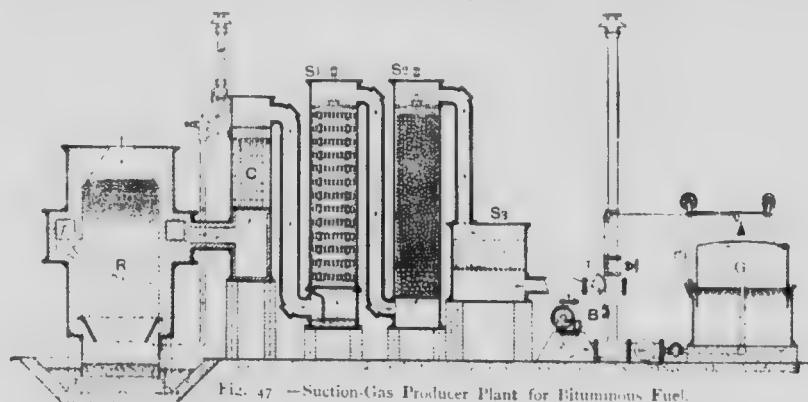


Fig. 47 — Suction-Gas Producer Plant for Bituminous Fuel.

lower part of the retort. This fire box is over a water-bottom from which the ash and clinker can be removed whilst the plant is working. Both streams of air, laden with the gases collected in their passage through the fuel, leave the retort by the same pipe *p p*. The result is that the new coal, just introduced into the hot retort, is heated to the distillation temperature whilst still in the upper part of the retort well above the outlet *p*, and the hydro-carbon gases produced pass down through the much hotter fuel below, and are there dissociated and partly oxidised, more or less completely, into hydrogen and carbonic oxide, the aim of the design being to ensure that these chemical reactions shall be completed before the outlet is reached.

After leaving *p* the mixture of hot gases first pass through a cooler C, and give up some of their heat to the air which is being supplied to the lower part of the retort. The gases then pass on to the scrubbers, which are similar to those used for anthracite with the addition of a "wood-grid"

considered worth while to incur the extra expense and trouble of recovering them, and various patterns of gas-producing plant have been worked out for this purpose.

One of the best known of these is the "Mond" gas plant, a diagrammatic sketch of which is given in Fig. 479.* In this design the gas producer or retort is shown on the right-hand side. Into this retort there is introduced, through the hopper or bell at the top, common bituminous slack, which in the hot retort begins to undergo destructive distillation at once. The products of distillation in the first instance pass downwards into the hot zone of fuel below, which destroys the tar, converting it into a fixed gas. In this hot zone the fuel is acted upon by an air blast charged with a much greater amount of steam than is used in the other methods. The air for this mixture of air and steam is driven through the apparatus by the "air blower," passing on its way first through the "air heating and saturating tower," where it

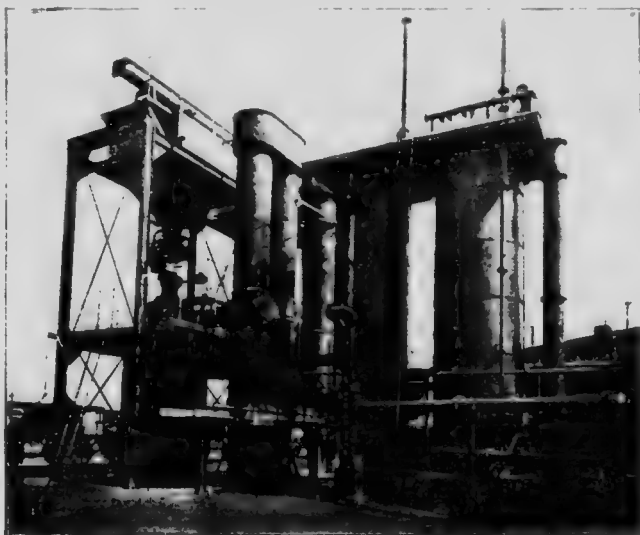


Fig. 480.—"Mond" Gas Producer for Midland Railway Power Station.

encounters streams of hot water trickling downwards, and becomes warmed and saturated with moisture. It then passes, as shown by the arrows, between the inner and outer tubes of the "regenerators" and inside the outer casing of the "producer" to the bottom of the latter, where now thoroughly well heated and charged with water vapour, it is discharged upwards through the fuel. The hot gases from the fuel, including undecomposed steam, pass through the tubular regenerators at the side in the opposite direction to the incoming air and steam, heating the latter, and being themselves cooled somewhat during their progress through the regenerators. After passing the regenerator the mixed gases, now well cooled, pass through the "washer" on their way to the

* Reproduced from Robinson's "Gas and Petroleum Engines," by the courtesy of Messrs. E. and F. N. Spon, Limited.

ammonia recovery tower, the left-hand one of the three tall towers shown in the diagram. In the washer the gases have intimate contact with a water spray, thrown up by revolving blades, and therefore the gas which passes into the ammonia recovery tower is heavily charged with moisture. This tower is lead-lined and filled with tiles, over which there is a constant downward flow of acid liquor circulated by pumps. This liquor consists largely of sulphate of ammonia associated with a little excess of free acid which combines with the ammonia of the gas, which is thus removed. The

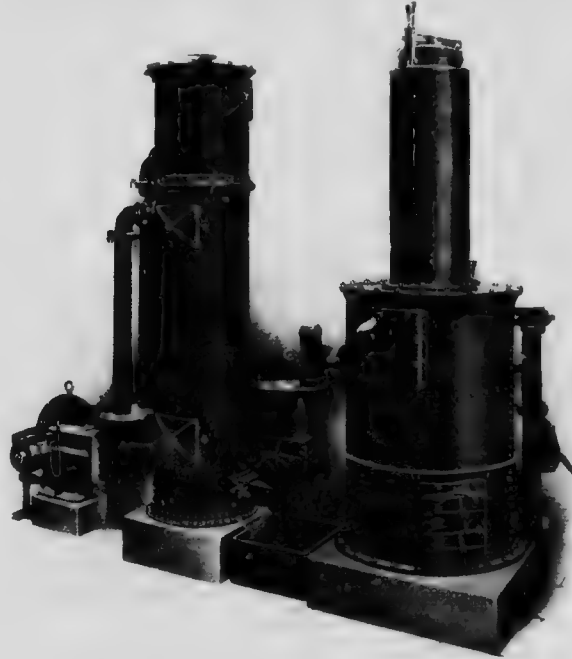


Fig. 481.—Crossley's Wood Refuse Gas-Producer Plant.

ammonia-free gas is conducted from the top of the ammonia recovery tower to the bottom of the gas-cooling tower, in passing up which it meets a downward flow of cold water, thus further cooling and cleaning the gas before it passes to the gas engines in which it is to be used. The heated water of the gas-cooling tower collected at the bottom is utilised in the third tower, marked on the diagram as the air-heating tower, and

through which the air blast from the fans is blown on its way to the producer, as already described. Various pumps and other apparatus required in the process are shown in the diagram, but space does not permit of further description. The general result is that cheap fuel is used, and the commercially valuable ammonia constituents are recovered.

A view of a "Mond" producer erected at Heysham for the power station of the Heysham and Lancaster section of the Midland Railway Company is given in Fig. 480. There are two such producers in the station, each capable of supplying sufficient gas for an output of 750 to 1,000 H. P.

Suction Plant for Low-Grade Fuel.—The solution of the problem of using low-grade fuels in gas producers has been carried a step farther

in the successful design of plants which can be fed with wood refuse. In wood-working factories and carpenters' and cabinet-makers' shops great quantities of sawdust, chippings, shavings, and other wood refuse are produced. A producer plant designed by Messrs. Crossley Bros., Limited, for utilising this fuel is shown in Fig. 481. Though it generally resembles the plant previously referred to, there are some important differences. In the first place, as the fuel itself contains a great quantity of moisture, no separate steam supply is necessary. The long, narrow neck between the hopper and the generator enables the new fuel to be dried and partly desiccated before it reaches the generator. The small cylindric box interposed between the generator and the bottom of the scrubber is a dust-collecting box over a water seal for the purpose of removing the numerous dust particles which are inevitably carried over with the gas. The scrubber is in two parts, the longer and lower part being the wet coke scrubber and the shorter and upper part the dry sawdust scrubber. After passing through the former of these the gas enters the centrifugal tar extractor seen on the extreme left, which removes the tar before the gas passes for a final drying to the wood-wool or sawdust scrubber mounted on the top of the coke scrubber. By these means the gas is efficiently freed from tar and other deleterious constituents, so that no trouble is experienced when it reaches the gas engines.

Quite recently successful attempts have been made to obtain a fuel suitable for gas-engine use from the heavy oils which, because of the presence of complex ingredients such as asphaltum, cannot, by the use of ordinary carburettors, be burnt directly in an internal combustion engine. The method adopted is a special gas-producer plant from which a gas is obtained having a calorific value of 200 to 250 B. TH. U. per cubic foot and free from deleterious compounds. Its fuel constituents are chiefly carbon monoxide, hydrogen and methane.

Other Gases Available.—Another kind of gas available for gas-driven stations, is the waste gas from our numerous blast furnaces and coke ovens. Space will not permit a description of the methods used for collecting and cleansing these gases, and we shall therefore conclude these preliminary remarks on available gases with a table of their calorific values as heat producers when completely burnt under good conditions.

Oil gas	..	..	..	..	..	..	1,340	B. TH. U. per cubic foot
Natural gas	..	..	..	..	..	..	900 to 1,000	
Coal gas	..	..	..	..	..	..	560 to 680	
Carburetted water gas	..	..	..	..	..	..	550 to 640	
Coke oven gas	..	..	..	..	..	..	480 to 540	
Gas from heavy mineral oils	..	..	..	..	..	..	200 to 250	
Producer gas	..	..	..	..	..	..	135 to 160	
Blast-furnace gas	..	..	..	..	..	..	95 to 120	

The British Thermal Unit (B. TH. U.), the unit of heat employed in the above table, is the quantity of heat required to raise the temperature of one pound of cold water from 60° to 61° F. It is the unit usually adopted by English engineers, and was the unit used by Joule in his classical experiments on the mechanical equivalent of heat. The corresponding values in the metric system can be obtained by multiplying by 9 (more accurately by 8.43), which will give calories (*see* page 223, Vol. I.) per litre or kilocalories per cubic metre. In all cases the volume of the gas is to be measured at standard temperature and pressure (0°C. and 760 mm.).

The fluctuations in the range of calorific values for the different gases is considerable and, incidentally, it is obvious that with the gases of lower calorific value larger cylinders and engines will be required to produce the same amount of power at the same speed, since a greater quantity of gas will have to be passed through the engine in a given time. This consideration, however, has not prevented the development of large gas engines for the use of blast-furnace gas, the poorest gas in the table (*see* page 377).

Actual Generating Stations.—When we turn from the fuels available for gas-driven stations and the methods of preparing those fuels to the generating stations themselves, we find that, compared with steam-driven stations, the number of public-supply stations which are gas-driven is very small, and moreover that none of them can compare in size and importance with its steam-driven rivals of even moderate size. The chief reasons for this will be referred to later; at present it is mentioned to explain why the gas-driven stations illustrated are so different in importance from the steam-driven stations described on pages 432 to 459. The number of stations available for our purpose is small, and the majority only handle small quantities of power much smaller, in fact, than the power handled by some of the stations described in Section II. ("Arcillary and Special Electric Supply Stations"), and in many cases not rising above 200 or 300 kilowatts. Two of the special stations, already described, Messrs. Cammell, Laird and Co.'s (page 375), and that at the Coltness Iron Works (page 376) are larger than this. Even the generating station at the Northampton Polytechnic Institute, London (page 378), is comparable in the quantity of power which can be handled with some of these small public-supply stations. In what follows we must, therefore, be content to illustrate the application of the principles involved on a comparatively small scale.

As an example of a station driven by producer gas we select the power station of the Taikoo Dockyard and Engineering Company, Limited, of Hong-Kong. Although the greater part of the power produced is used by the company itself, yet some power is sold to adjoining works, and to that extent the station is a "public-supply" station.

Notwithstanding the fact that this station (a ground plan of which is

given in Fig. 482) is in the Far East it is a station installed and equipped by British engineers. The gas-producing plant consists of three "Mond"

producers erected by the Power-Gas Corporation, Limited, of Stockton-on-Tees. These producers are designed in accordance with the principles already explained, though they contain important modifications in certain details. Besides supplying gas to the power station they also supply gaseous fuel to various furnaces and stoves used on the works.

The gas-engine plant supplied by Richardsons, Westgarth and Co., Limited, of Middlesbrough, has a total output of 3,300 B. H. P. It consists of two 1,100 B. H. P. twin tandem "Cockerill-Westgarth" engines, A and B in Fig. 482, and two 550 B. H. P.

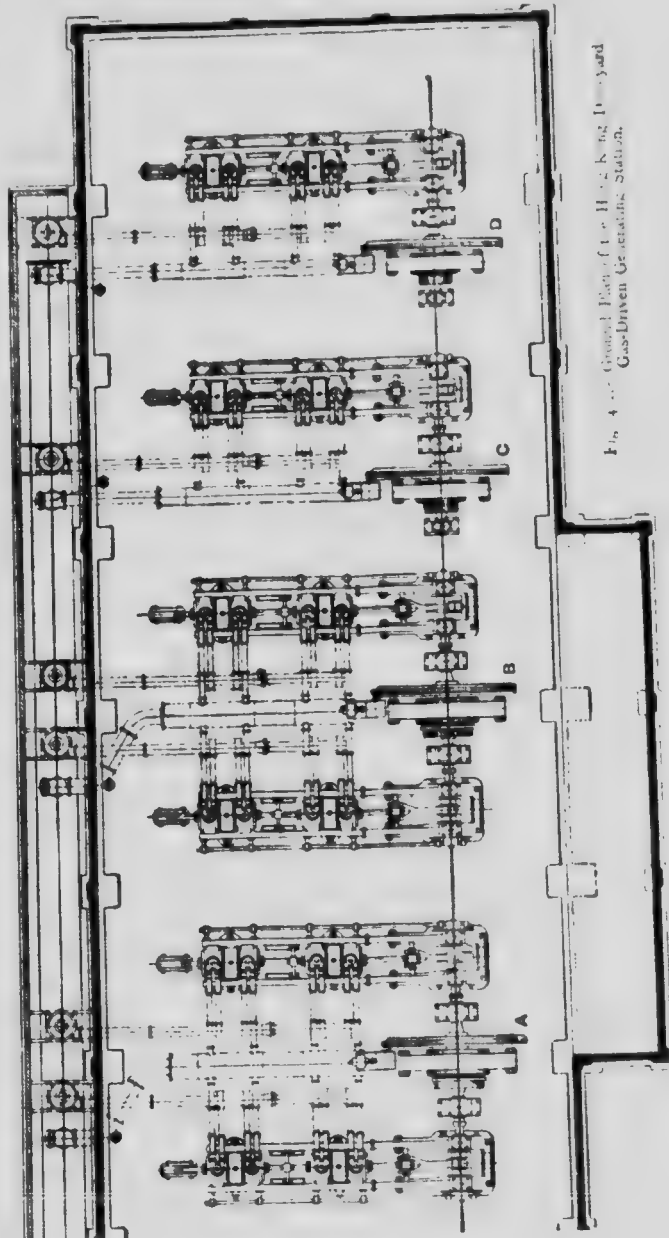


Fig. 482. Ground Plan of the H. K. King Power Station, Gas-Driven Generating Station.

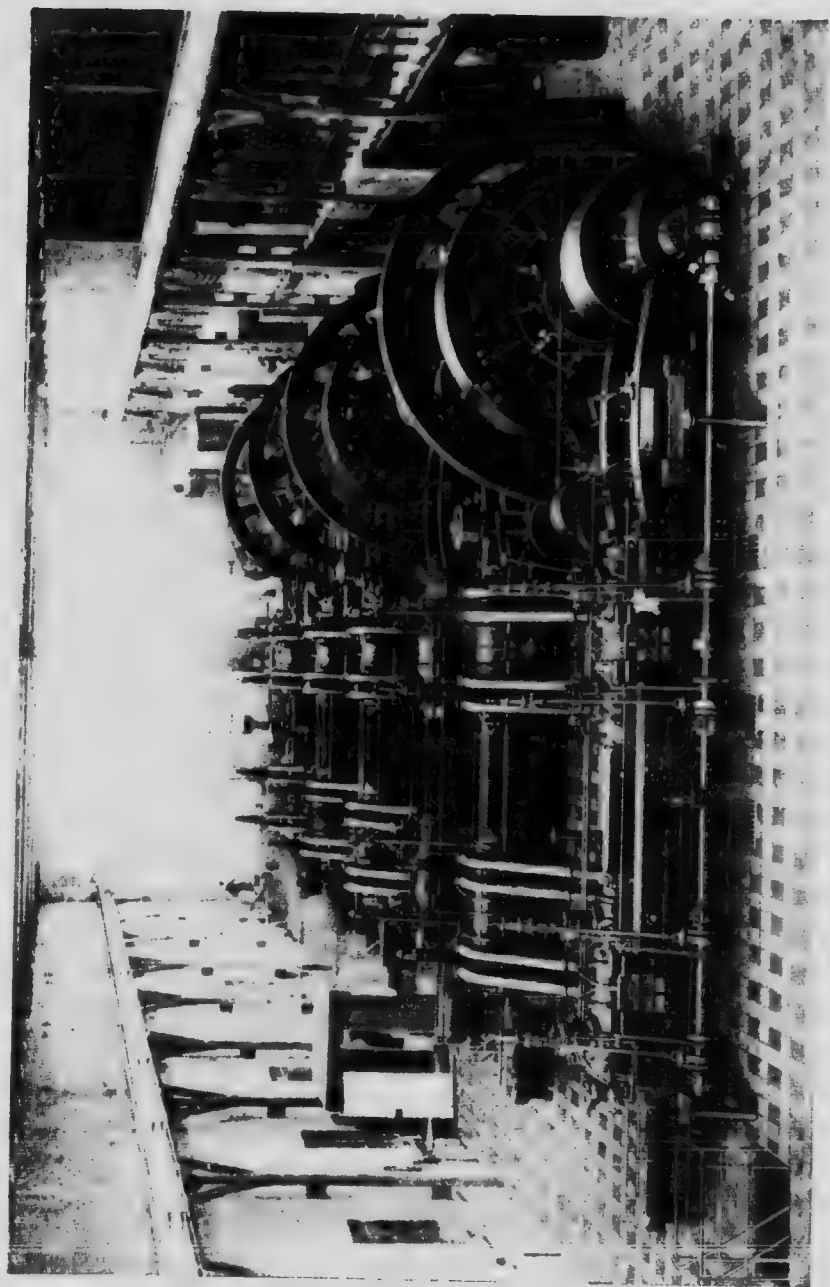


Fig. 483.—Interior of the Hong Kong Do. Kyard Gas-Driven Generating Station.

single tandem engines of the same type, c and d in Fig. 482. The cylinders, which are double acting, are all 25½ inches in diameter, with a stroke of 31½ inches, and run at 120 R. P. M. In this way interchangeability and a reduction in the number of spare parts are secured, which is a great advantage when plant is sent to a colony so distant as Hong-Kong.

For starting purposes a motor-driven compound compressor stores air at 200 lb. pressure in a large steel receiver when the plant is running, this receiver being large enough to turn any one of the engines through

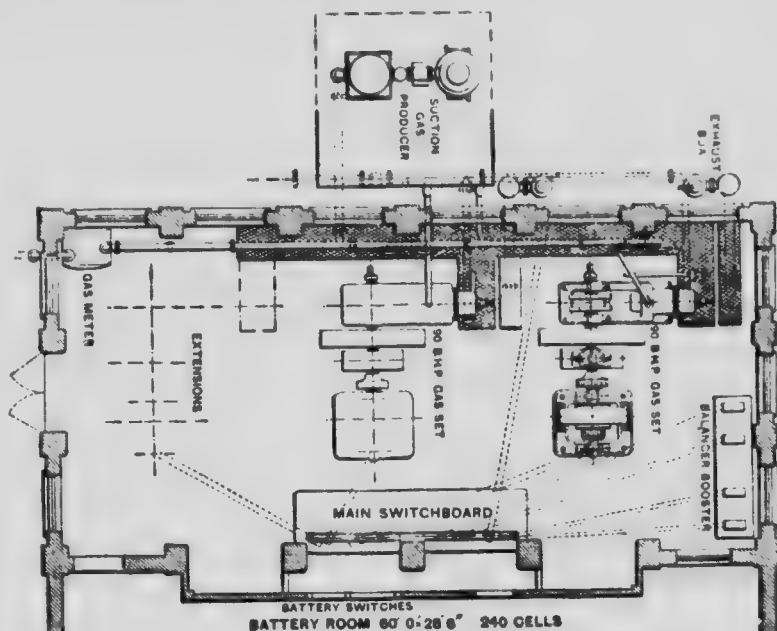


Fig. 474.—Plan of the Ascot Gas-Driven Electric Generating Station.

several revolutions at starting. The supply of pressure air is, of course, disconnected as soon as the engine is under way. The producer gas obtained has a calorific value of 140 B. TH. U. per cubic foot, and the guaranteed gas consumption is 68 cubic feet per B. H. P. hour.

Generators are 750-kilowatt Dick, Kerr continuous current machines, placed between the twin tandem engines in the larger sets, and similar 375-kilowatt machines in the single sets. The full-load rated output of the station is therefore 2,250 kilowatts. Fig. 483 gives an excellent view of the interior of the station.

The general arrangement of a small public supply power station using producer gas from a gas producer is shown in Figs. 484 and 485, which

represent in plan and sectional elevation a small power station at Ascot erected by the Ascot District Gas Company. The amount of power handled is not large, since the two engines shown in the plan have only an

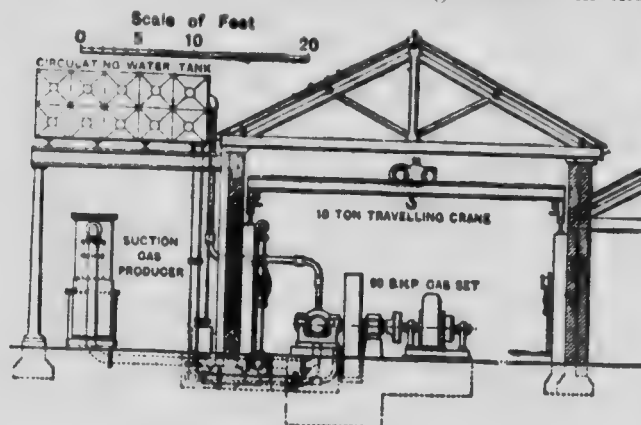


Fig. 485.—Sectional Elevation of the Ascot Station.

output of 90 B. H. P. each, the generators being 50-kilowatt machines. An external view of the station is given in Fig. 486. The illustrations are instructive from the point of view of showing the small relative space occupied by the gas-producer plant, which takes the place of the boiler plant of a steam-driven station. The tank mounted on girders in Fig. 485 is the water tank which supplies the water for the producer, and also the circulating water for cooling the gas engines. The fuel used in this station is the coke produced in the gas works of the gas company which erected the station, and it is interesting to note that although the proprietors of the station are manufacturers of coal gas, they preferred to put down a gas-producing plant for the power station rather than use the more expensive coal gas produced at the gas works.



Fig. 486.—The Ascot Gas-Driven Electric Supply Station.

A gas-driven public-supply station dealing with a somewhat larger amount of power has been erected at Hitchin, in Hertfordshire. The total

output of 90 B. H. P. each, the generators being 50-kilowatt machines. An external view of the station is given in Fig. 486. The illustrations are instructive from the point of view of showing the small relative space occupied by the gas-producer

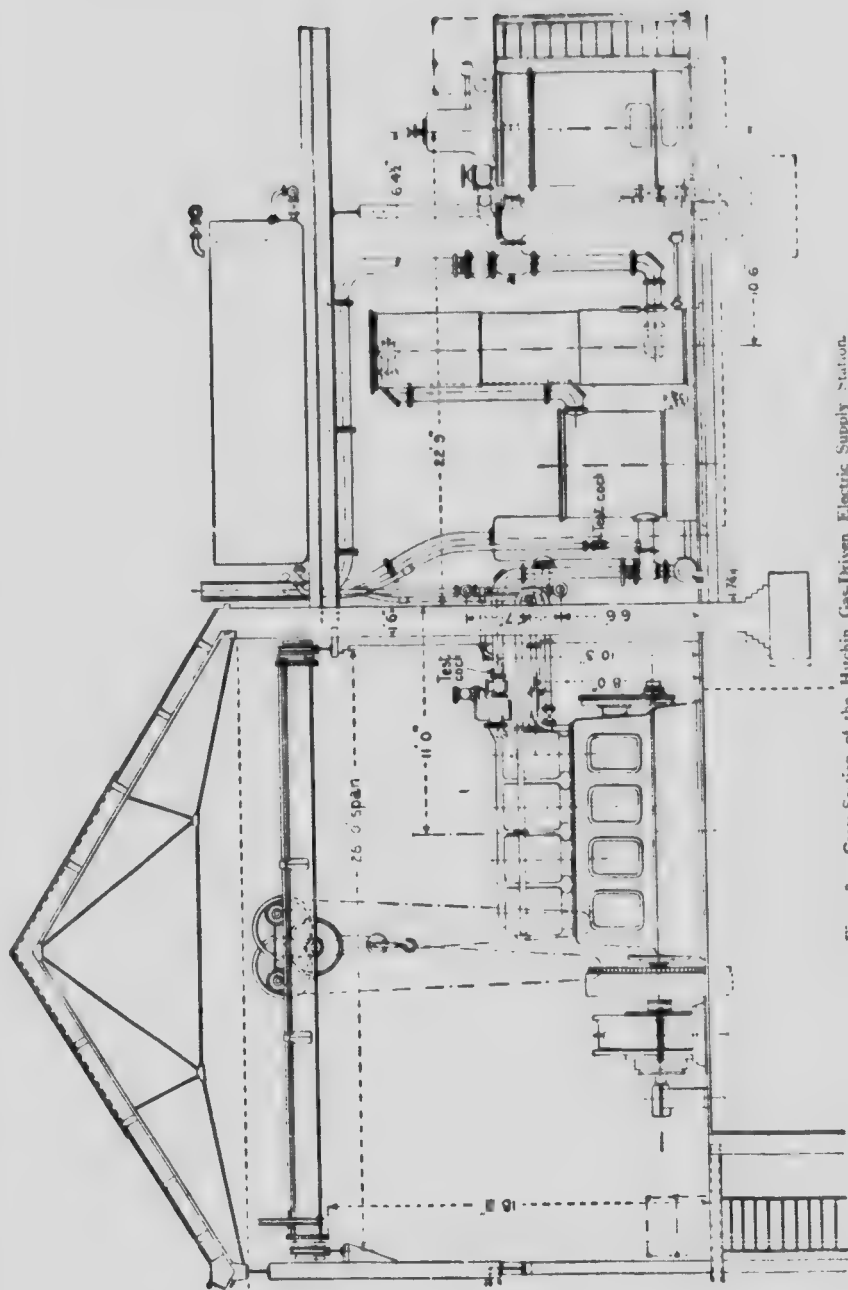


Fig. 487.—Cross-Section of the Hutchin Gas-Driven Electric Supply Station.

output of this station is 265 kilowatts, which is given by three distinct sets of gas plant of 165, 60 and 40 kilowatts respectively. The station is driven by producer gas from plants using anthracite coal, erected for the largest and smallest sets by the Campbell Gas Engine Company, who also supplied the engines; the producer and engine for the 60-kilowatt set was supplied by the National Gas Engine Company. All the dynamos are Crompton dynamos direct-coupled to the gas engines, and of types

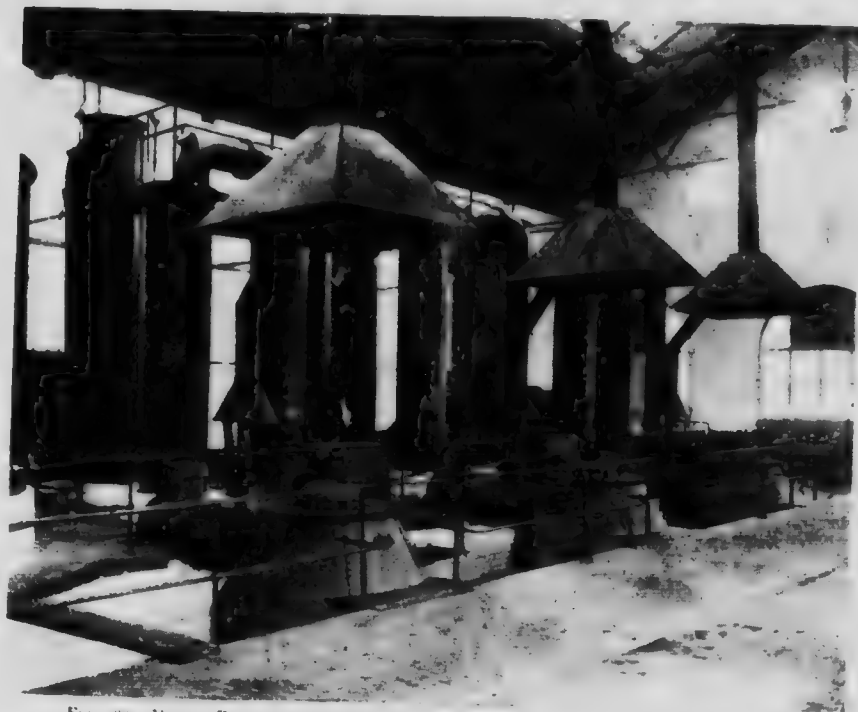


Fig. 486. Dowson Pressure Gas Producers at Euston Station, London and North Western Railway.

illustrated and described in previous pages. The supply is c. c. three-wire, with 480 volts across the outers. A vertical cross-section of the station through the 165-k. w. set, and its gas-producer plant is given in Fig. 488. It will be noticed that the gas plant is quite close to the engine, but, of course, outside the engine room. The purpose of most of the details of the gas plant will be obvious from the preceding general descriptions, and the chief dimensions are given in the drawing. The producer plant shown in the figure is rated at 250 H. P., and supplies gas to the vertical four-cylinder gas engine only. Beyond the engine room the building is extended to provide a battery room in which there is a Pritchetts and Gold secondary battery of

40 cells to take the night and the light day loads, as well as to help the generating plant over the peak of the load curve. This battery can give an output of 23 kilowatts for 10 hours.

An example of a much larger plant is given in Fig. 488, which shows three sets of Dowson pressure-gas plants each capable of supplying gas to engines giving 300 B.H.P. This illustration is reproduced from a photograph of the plant installed by the Dowson and Mason Gas Plant Company



Fig. 489.—Cleansing Plant for the Gas Producers at the Walthamstow Electric Supply Station.

Limited, to supply gas for the generating station used for lighting the well-known Euston station sidings and goods yard of the London and North Western Railway Company. The tops of the retorts are seen in the figure, with the charging platform and the various scrubbers.

The fuel is fed into each producer through the small hopper shown at the top. The large hoods over the hoppers are to carry away safely any hot gases or fumes which escape from each retort during the few seconds the top of the hopper is open to receive a charge. In the back of the illustration there are the various cooling and cleaning or scrubbing appliances, through which the gases pass on their way to the gas engines.

The plant is of the pressure type worked with a jet of superheated steam.

The cleaning and cooling appliances for part of a Dowson pressure plant are shown more clearly in Fig. 489, which is a view of these appliances as erected outside the producer house of the Walthamstow electricity station. In this station gas engines having a total output of 3,000 B. H. P. are driven by producer gas. The producers are just inside the wall of the building, and the gases from them pass first through cooling tubes, and then through the cylindric coke scrubbers S S, the general construction and action of which have been already described. From the coke scrubbers the gases pass to the sawdust scrubbers D D, on leaving which they are passed into a small gas holder and then into the gas main.

An interesting modern development of the use of producer gas is the supply by a public company of such gas which cannot be used directly for lighting purposes, but through the medium of electric plant can be made available for the supply of current which can be so used. An example of this utilisation of producer gas is given by the Wednesbury Corporation Electricity Works, which purchases producer gas from the South Staffordshire Mond Gas Company, and supplies the district with continuous current at 230 volts for lighting, and 460 volts for power purposes. The interior of the station is shown in Fig. 490, and for the following particulars the author is indebted to Mr. W. Farnell, the engineer and manager. The gas used has a calorific value varying from 135 to 150 B. TH. U., and is delivered at a pressure of 5 lb. per square inch into a gas holder of 600 cubic feet capacity, which, however, is only employed as a governor to keep the pressure constant at the engines. The supply pressure is reduced to a pressure of $3\frac{1}{2}$ inches of water by reducing valves operated by the gas holder. The consumption of gas averaged over the whole year is 125 cubic feet per kilowatt-hour generated. The over-all heat efficiency is therefore about 19 per cent. if the mean calorific value given above be adopted.

The station was started in 1908 with two Westinghouse engines, each of 220 B. H. P. of the vertical tandem type, with four cylinders and two cranks. A third similar engine, but with six cylinders and three cranks with an output of 350 B. H. P. was added in 1911. All these engines have pistons of $16\frac{1}{2}$ and $15\frac{1}{2}$ inches in diameter, with a stroke of 16 inches, and run at 300 R. P. M.; their working parts are interchangeable, and they have forced lubrication for their bearings. Each drives a direct-coupled C. C. dynamo, the total B. H. P. being about 800.

Quite recently (1913) a double-acting Fraser and Chalmers engine of 400 B. H. P. has been installed and runs at a speed of 140 R. P. M. The diameter of the piston is 28 inches and the stroke 34 inches. For the present it drives a high-speed 250-kilowatt continuous current dynamo by a rope drive of ten cotton ropes, but when the load increases sufficiently

a second tandem cylinder will be added, increasing the output to 840 B. H. P. The rope-driven high-speed dynamo will then be replaced by a machine directly coupled to the shaft, and the present dynamo used as the C. C. machine in a motor-generator set. The station plant also includes a secondary battery which can take the load from midnight to 6.30 a.m., and the day load on Sundays.

The station delivers about 1,000,000 kilowatt-hours per annum, of



Fig. 490.—The Wednesbury Electric Station, driven by Mond Gas from Public Mains.

which about two-thirds is for power purposes. Owing to the large proportion of the power load, for which the charge varies from 3d. to 1½d., the average selling price is only 1.35d. per kilowatt hour, but notwithstanding this there is a margin after paying all working expenses and the interest on and repayment of loans. It is an achievement to be able to show such a good result, and to be free from the worry and nuisance of either a boiler house or a producer plant.

Use of Blast-Furnace Gas.—The waste gases from the blast furnaces in large ironworks have been scheduled above (see page 469) as a source of power for the generation of electric energy, and a brief description of one instance of their utilisation has been given in the preceding pages (see page 376 *et seq.*). From the nature of the case a supply of such gas for

the use of a separate "public-supply station" cannot be expected to be available, but this section would scarcely be complete without some refer-

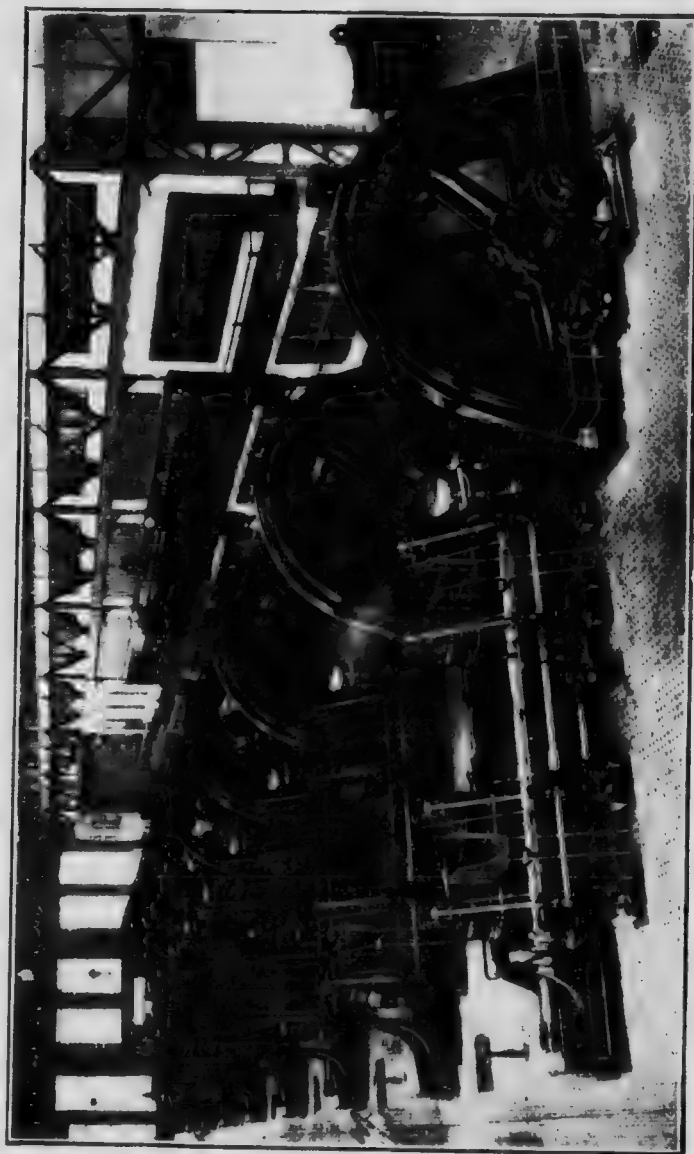


Fig. 491.—13,000-Kilowatt Generating Station driven by Blast-Furnace Gas.

ence to the production of electric power on a large scale in which these waste gases are used, notwithstanding the fact that the power so generated may

be entirely used for the industrial purposes of the works in which the generating station is established. We shall therefore conclude this sub-section with a brief description of one such installation.

The example selected is the generating station of the Adolf Emil Hütte Steel Works at Esch, Luxemburg, and a view of the interior of the station is given in Fig. 491. In this station there are nine large gas engines of the double-acting four-cycle tandem type, each designed for an output of 2,100 H. P. when supplied with the waste gases from the blast furnaces of the works. These gas engines are fired by the current from a 65-volt 25-kilowatt generator or from a small secondary battery, there being also a duplicate generating set as a reserve. The gas engines run at 64 R. P. M., and each drives a three-phase generator having an output of about 1,450 kilowatts at 5,300 volts and 50 ω with a power factor of 0.65. The excitation is supplied by a 330-kilowatt continuous current generator, which is also in duplicate, and generates a 500-volt excitation current.

The gas for these engines and for the gas engine-driven blowers for the furnaces is obtained from six blast furnaces, whose number is to be increased to eight, and then the electric generating station will be extended and will contain fourteen machines, although only ten will be required to supply power to the works at their maximum output. The remaining four sets will act as spares, or may perhaps be utilised to supply power to adjacent works, in which case the station will become a public supply station. The total possible output of the gas engines will then be 30,000 H. P., which means that each blast furnace can furnish 3,750 H. P., in addition to the power required to drive its own blowing engines. These figures show how very important it is that such a source of useful power should not be neglected by allowing the gas to be wasted, or worse than wasted, inasmuch as its presence in the atmosphere does not improve the vegetation of the surrounding country, as we know to our cost in our own "Black Country."

Use of Natural Gas.—An example of a public supply station driven by natural gas is given in Fig. 492, which shows the interior of the station erected by the Independence Electric Company, of Independence, Kansas. The natural gas, which is obtained from the Oklahoma fields, some miles distant, has a calorific value of 950 B. TH. U. per cubic foot, which compares favourably with the heat obtainable from ordinary town gas, and is much higher than the calorific value of ordinary producer gas. The gas supply lines deliver the gas at the high pressure of 3.5 lb. per square inch, which, by means of reducing valves and intermediate gas holders is reduced to the equivalent of 3 or 4 inches "head" of water before it reaches the engines.

The gas so supplied is used to drive three different gas-engine sets. The largest is a 500-kilowatt twin tandem double-acting engine, coupled





Fig. 49a.—Electric Generating Station in Kansas driven by Natural Gas.

to a 2,300-volt, 60-cw, three-phase alternator. The second set consists of a similar but smaller gas engine, by a different maker, driving a 200-kilowatt General Electric Company's alternator at 300 R. P. M., whilst the smallest set consists of a 100 H. P. Westinghouse vertical three-cylinder gas engine, driving by a belt a 75-kilowatt General Electric Company's alternator. The last-named set was the pioneer set, but it is now used only as a stand-by in case of a breakdown. The average consumption of gas by the large engines on a thirty-day test under all conditions of load was 20 cubic feet per kilowatt hour, but on a special test at 50 to 60 per cent. of full load the kilowatt hour was obtained with a little over 16 cubic feet of gas, giving an over-all energy efficiency of about 22.5 per cent., the thirty-day test giving an efficiency of about 18 per cent.

Gas v. Steam.—It has been pointed out above that the number and the importance of the public electric supply stations which are gas driven are insignificant compared with the steam-driven stations. For this position there are many reasons, chief amongst which must be placed the much earlier development of steam engines and steam-raising plant as compared with the development of gas engines and gas-producing plant, by which the minds of engineers were directed to the former and to the perfection of the machinery and appliances connected therewith long before the latter could be considered as, in any sense, a rival where large quantities of power had to be handled. Thus, notwithstanding the fact that the actual amount of mechanical energy obtainable from a ton of coal is much greater when gas and gas engines are intermediaries than with steam and steam engines, the number of public supply stations employing the latter as compared with the former is simply overwhelming, and a new lease of precedence appears to have been given to steam by the recent developments of steam turbines, though none of these is as efficient a power transformer as its gas rival of much smaller size.

As incidental to the above it may be added that the successful design and building of large gas engines, for say, 1,000 H. P. and upwards each, is very recent indeed, and these, with their rivals already in possession, have still to persuade the majority of engineers to forsake their old and tried machines for the new-comers, a change which, in view of the large amount of capital sunk in steam and steam-driven plant, could only be made gradually, if made at all.

The position, however, as in most engineering problems, is much more complicated than appears at first sight, and we can only indicate the chief points here. In the first place it is a somewhat startling fact that even the best equipped steam-driven generating station can only pass on to the busbars of the switchboard about 10 or 11 per cent. of the energy of the coal fed into the furnaces. On the other hand a gas-driven station, as figures given above show, can double this percentage and thus effect

a large saving in the fuel bill for a given output. But the charge for fuel is only one of the items in the cost of producing electric energy, and is overshadowed, more especially in small stations, by other "running charges." Taking an example at random from published data in a particular year the fuel cost, averaged over the whole year, at the generating stations of the Manchester Corporation was 0.24d. per kilowatt hour, whereas the total running charges including wages, oil, and other stores and repairs, were 0.49d. per kilowatt-hour sold, to which must be added rent, rates and taxes, management charges, and

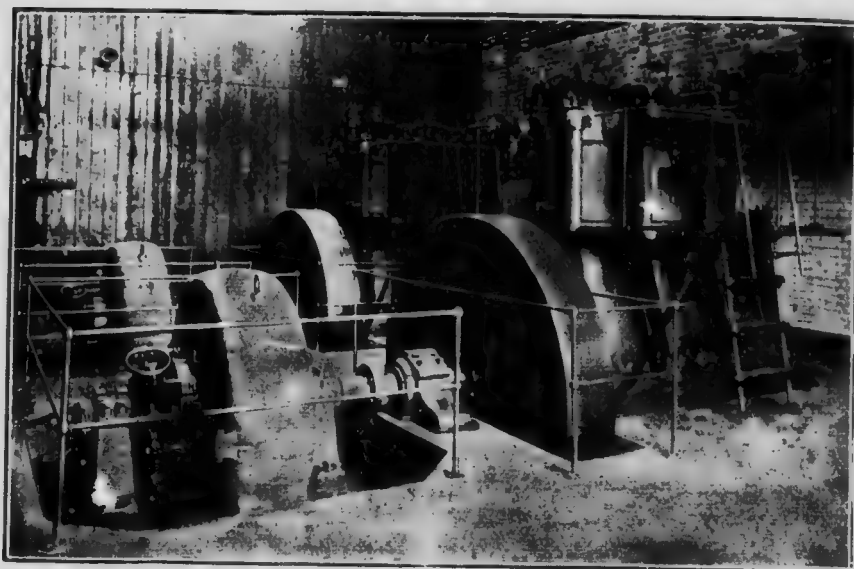


Fig. 493.—The Chichester Oil-Driven Electric Supply Station.

interest on capital spent on buildings and machinery. The example given is a favourable one for steam because of the magnitude and efficiency of the system, and the charge for fuel being low, owing to the proximity of the coalfields. It will be noted, however, that apart from standing establishment and permanent items, the other running charges are as important as the cost of fuel, and therefore it is obvious that a saving in fuel due to a change of system may be masked by an increase in the other running charges. Unfortunately no data are available from large gas-driven stations which can enable a fair comparison to be made. Having regard, however, to the large stations now being operated with blast-furnace gas it would appear that the time is quite ripe for a large public-supply gas-driven generating station to be put down in this country, from which much valuable data for further progress could be obtained. Meanwhile the advocates of

steam assert that any saving of fuel obtained by the use of gas is more than counterbalanced by increased expenditure in other directions, and especially in the items for repairs and renewals, and for oil. The effect on the wages item is also a source of controversy. On the other hand the capital charges for land and buildings must be appreciably less for the gas-driven stations, because of the much smaller space required for the producer plant as compared with steam-raising plant, but part of this saving will be lost by the greater space required by gas engines as compared with steam engines, especially steam turbines. This extra space will probably be saved if and when a satisfactory gas turbine has been evolved.

Oil-Driven Plant.—Where mineral oil is directly used as the fuel of an internal combustion engine there is no elaborate plant or machinery for the preparation of the fuel for the engine, a comparatively small carburettor or other device being all that is required. A favourable instance of this is the ordinary petrol automobile, in which the apparatus corresponding to the boiler plant of the steam engine is reduced to an oil storage tank and a carburettor. On the other hand, the price of oil, under present conditions, is liable to violent fluctuations, which makes engineers unwilling to rely entirely upon it. The plan of an electric power station using oil-driven engines, therefore, is reduced to the engine room itself, and a view of such an engine room at the Chichester electric power station is given in Fig. 403. In this figure there are shown two Mirreles-Diesel oil engines coupled direct to two 100-kilowatt 500-volt C.C. generators running at 250 R.P.M. The chief accessories not shown in the illustration are the pumps for supplying the circulating water for cooling the cylinders, for which about 600 gallons an hour are drawn from and returned to an adjacent canal. The other accessory is the fuel-supply tank, which corresponds to the coal bunkers of a steam-driven station, and in this instance is a circular tank of 6 ft. 9 in. diameter by 12 ft. 4 in. in height, which is close to the engine room, and can contain sufficient fuel to run both engines for a week. The oil is, of course, supplied from the tank to the engines without being handled.

IV. (iii).—WATER-DRIVEN (HYDRO-ELECTRIC) STATIONS

The third type of public supply station, which will now be considered, stands in importance next to the steam-driven type, and, at present, a long way ahead of the gas- and oil-driven type of station. In one respect it is from the economic standpoint the most interesting of the three types, inasmuch as in generating electric power from the energy of rivers and waterfalls we are not, as in the case of fuel, using up our capital accumulated during long periods of geological time, but living, as it were, very closely upon our income. The ultimate source of the energy in both cases is the sun, but our fuel represents solar energy which reached the earth in long

past milleniums, whereas the energy of our rivers and waterfalls came to us from the sun within the past two or three years at the farthest, and fresh stores of similar forms of energy are being daily prepared for our use.

We are, however, now concerned with the processes and their details by which this recently stored energy is made available for the service of man by its conversion into electrical energy through the medium of electric generators driven by water motors. The amount of hydraulic energy available at any given point depends upon two factors, namely, (i.) the

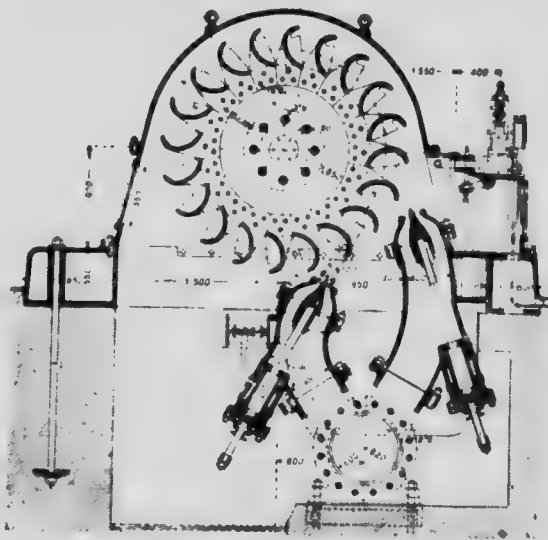


Fig. 494.—Cross-Section.

Impulse Water Turbine, 6,000 H.P.

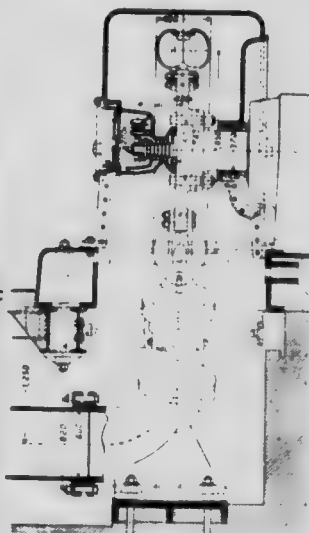


Fig. 495.—Longitudinal Section.

available quantity of water, and (ii.) the available fall or "head" as it is technically called. This "head" corresponds to the pressure or voltage in the electrical case, and if the pressure in the water can be obtained by pumps, accumulators or other devices, an actual vertical fall of so many feet is not necessary. We are, however, dealing here with the utilisation of natural supplies of raised and stored water, and to utilise their energy, due to the fact that such water has been raised above sea-level, it is essential that, in the process, the water should be dropped to a lower level. The greater the amount of the vertical drop the greater is the amount of energy which can be obtained from a given quantity or weight of water.

The use of water wheels or water motors to obtain mechanical power from falling water is of great antiquity, but where large quantities of power have to be handled the old-fashioned water-wheel, whether overshot or

undershot, or any other variety, has been superseded by the turbine. Of this type of water motor there are two chief varieties (i.) the impulse turbine, and (ii.) the reaction turbine.

In the first, the impulse type, a jet of water is directed against a series

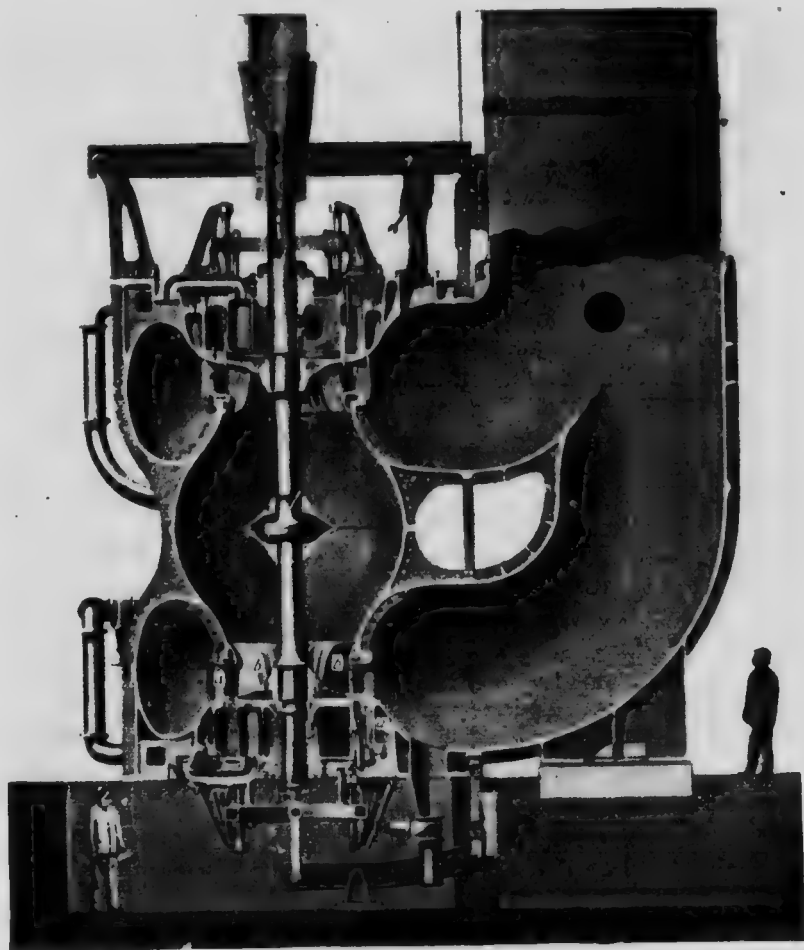


Fig. 496.—Section of Vertical-shaft Reaction Water Turbine, 13,000 H. P.

of buckets set upon the periphery of a wheel; the position of the nozzle producing the jet being fixed, the wheel, which is, of course, free to move, is driven round, and power can be obtained directly or indirectly from its shaft. The rotor of such a turbine capable of developing 6,000 H. P. at 375 R. P. M. has already been illustrated in Fig. 25b, page 257. To give a

better idea of the details and of the dimensions, Figs. 404 and 495, are vertical sections at right angles to and along the axle or shaft of the same rotor. There are twenty buckets and two jets of water, one of the jets being at an angular distance relative to the axis of rotation of about



Fig. 497.—Cross-Section of a 10,000 H. P. Reaction Turbine.

45° behind the other, so that as regards the position of the buckets the two jets are not in the same phase. The dimensions given on the drawings are in millimetres, and some of them are very interesting. Thus the main supply pipe bringing the water to the turbine is 600 mm. (23.6 in.) in diameter internally, the two branch pipes, one for each nozzle, being 400 mm. (15.75 in.) in diameter, the buckets are 490 mm. (19.3 in.) wide overall, and their tips are on a circle 2,260 mm. (7 ft. 5 in.) in diameter. What may be called the pitch circle at which, on the average, the effective impact of the water is delivered has a radius of 925 mm. (36.4 in.), which may be taken to represent the leverage at which the water acts in a tangential direction. The quantity of water issuing from the nozzles at a definite velocity is controlled by "needles," whose shape is clearly shown in the drawing, and which can be moved forwards or backwards, thus regulating the size of the opening. The water is brought to the wheel by pipes or penstocks in a manner described elsewhere (see page 501) the total head being 330 metres, or 1,080 ft. At full load the water delivered is 1,700 litres, or 375 gallons, per second.

The other general method employed in the reaction turbine is illustrated in Fig. 496, which is a vertical section through the vertical axis of one of the more recent turbines installed at Niagara by the Electrical Development Company of Ontario in a power-house on the Canadian side. These turbines are installed at the bottom of a wheel pit 138 ft. deep, and the water is brought down to them from the river above by the large vertical pipe or penstock seen

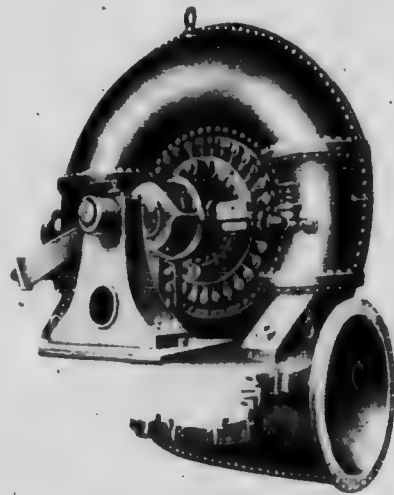


Fig. 496.—10,000 H. P. Reaction Turbine.

in the figure. This vertical stream of water is, it will be observed, divided into two streams at the bottom, for there are two turbines, an upper and a lower one, upon the shaft. The turbines are what is known as inward-flow turbines, that is, the pressure water encircling the periphery of the moving wheels as seen by the sections *A A* of the enclosing pipes is directed by fixed blades *a a* against the moving blades *b b* attached to the wheel. Both sets of blades are properly curved, so that the water enters the moving wheel without shock or eddies, and as it flows inwards forces the wheel blades round. Having given up the greater part of its energy it passes to the large central exhaust chamber *c*, and thence to the tail race, whence by means of a tunnel about 2,000 feet long it is carried to a point behind and beneath the celebrated Horseshoe Falls, where it is discharged into the river.

The turbine shown in Fig. 496 can develop 13,000 H. P. at 250 R. P. M., this power being transmitted by the vertical shaft, which is 115 feet long, to an 8,500-kilowatt generator in the power-house immediately over the wheel pit. This power house was designed to contain eleven of these sets, and will be referred to again later.

The way in which the water passes through the fixed blades to the moving blades, in a radial inward-flow turbine of the reaction type, can be better seen in Fig. 497, which is a section of a reaction turbine with a horizontal shaft capable of developing 10,000 H. P. The water enters from the penstock through the opening shown at the bottom, and flows round the outside of the wheel in a channel, which from being 55 inches in diameter at the entrance, gradually narrows as the water is delivered up to the wheel. The water is guided into the wheel first through a few fixed outer guide vanes *a a a*, placed fairly far apart, and then through an inner series of fixed guide vanes, thirty-two in number, placed close together, which completely encircle the moving wheel. The vanes on the latter, which slope in the opposite direction and receive the flowing water after it has passed the fixed vanes are thirty-four in number, so that the position of each moving vane relatively to the fixed vane opposite to it differs slightly from that of its predecessor, and there are no dead points. After flowing past the moving vanes and driving the wheel round, the water, deprived of its "head," enters the tail race, and is led away from the centre of the wheel. The external appearance of the wheel is shown

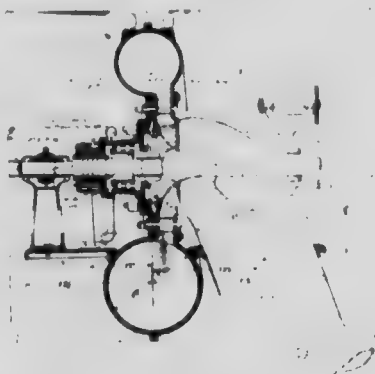


Fig. 499.—Longitudinal Section of 10,000 H. P. Turbine.

in Fig. 498, and a vertical section longitudinally through the shaft is shown in Fig. 499. This will enable the reader to make out further details, and especially the mechanism by which the angle of the thirty-two fixed vanes can be simultaneously altered to reduce or increase the supply of water to the moving wheel.

The above paragraphs and figures illustrate the chief two methods of converting the energy of falling water into mechanical energy by means of modern turbines. Both methods can be made to give excellent results and it is not uncommon to find wheels of each type using power-water drawn



Fig. 500.—Niagara Falls Power Company's No. 1 Station.

from the same source. It will be noted that the shaft of the turbine may either be vertical or horizontal; in fact, theoretically, it might be placed at any angle, but any other of the possible positions would be inconvenient, and lead to practical difficulties.

Niagara.—The "harnessing of Niagara," as it has been called, furnishes an excellent example of the utilisation, on a large scale, of this particular source of energy as made available for the service of man through the medium of electric-generating plant. Notwithstanding the fact, therefore, that much of the work at Niagara, especially in the earlier and more difficult stages, dates back, now, a fair number of years, it is worthy of consideration from several points of view. Amongst these may be mentioned the large amount of power which is actually handled electrically, and the illustrations which the various schemes adopted can furnish of the different methods of utilising the energy of a moderately high fall.

ELECTRIC POWER STATIONS AT NIAGARA

The complete history of the developments of the supply of electricity from Niagara, although fascinating in itself, would demand a greater amount of space than is here available, and therefore the technical allusions can only be the briefest possible. In the preliminary discussions which preceded the first attempt to utilise the energy of the falls on a large scale a prominent part was taken by an International Niagara Commission which met in London, and in which English engineers were prominent. Two general methods were available to



Fig. 501.—The First Three Large Alternators at Niagara.

"harnessed" the Falls. The power station with all its machinery might be installed on the bank of the river above the Falls; in this case, in order to utilise the head of the falls, the water wheels might be utilised, the water wheels or water motors could have been placed at the bottom of deep pits, and the water would have to be made to carry off the water by means of a tunnel or a pipe in the form of a tunnel discharging the water at a convenient point into the gorge below the Falls. The alternative method was to carry the water by canals or pipes, having their intakes above the Falls at a convenient position or positions at the top of the gorge, and to place the water motors at the bottom of the gorge, or to use the water itself, in which case the water when used could be let fall directly into the gorge. The Commission decided to recommend the latter method, and the first large power-house was designed

to carry it out, though it may be noted here that in later years, and after the success of the first attempt was assured, both methods have been used on a large scale on both sides of the river.

Another important recommendation made by the Commission was that the individual units should be of 5,000 H. P. each, a size which up to that time had not been constructed, and in the design of the details of which many new problems, electrical and mechanical, had to be solved.

The first large station to be erected and equipped was Station No. 1 of the Niagara Falls Power Company, which commenced to sell electrical energy in 1895. The station was above the Falls, on the American side, the turbines

being placed in a wheel pit about 160 feet deep, and the tail race being a tunnel, discharging into the gorge below the Falls.

An interior view of this station is given in Fig. 500, which shows the large generators arranged in a single row down the length of the room. They stand over the wheel pit just re-



Fig. 502.—Niagara Falls Power Company's No. 2 Station.

ferred to, their vertical shafts being driven by turbines placed near the bottom of the pit and discharging the used water into the tail-race tunnel. The separate units were of 5,000 H. P., generating two-phase currents at 2,200 volts and 25 ω at 250 R. P. M., and the station was designed to take ten of these its capacity therefore being 50,000 H. P.

One of these alternators, which are of the so-called "umbrella" type, has been described elsewhere (*see* page 261). A better view of the first three alternators erected is given in Fig. 501, which is reproduced from a photograph taken in 1896 in the early days of the construction and equipment of the station. The staircase seen in the foreground is the top of a stairway leading down into the wheel pit.

Even before the completion of this first station it became evident that the demand had been under-estimated, and a second station (No. 2) was very soon being designed to contain eleven additional sets, each of the same size as in station No. 1, namely 5,000 H. P. The two stations, therefore, were designed for a total capacity of 105,000 H. P. A view of the

exterior of No. 2 power house, reproduced from a photograph taken in 1903, when six of the new generators had been installed, is given in Fig. 502.

This view is taken from the end remote from the river, the length of the house being parallel to a fore-bay or canal practically at right angles to the river. The interior is very similar to that of No. 1 (Fig. 500), the chief difference being that the iron bridge over the generators has been abolished, being unnecessary in the later machines, as the collector rings are placed at the bottom of the dynamo shaft instead of at the top. The remaining five-generators for the completion of the equipment were however of the internal revolving-field type, so that the two houses contain working examples of three stages of the development of large vertical shaft hydro-electric alternators.

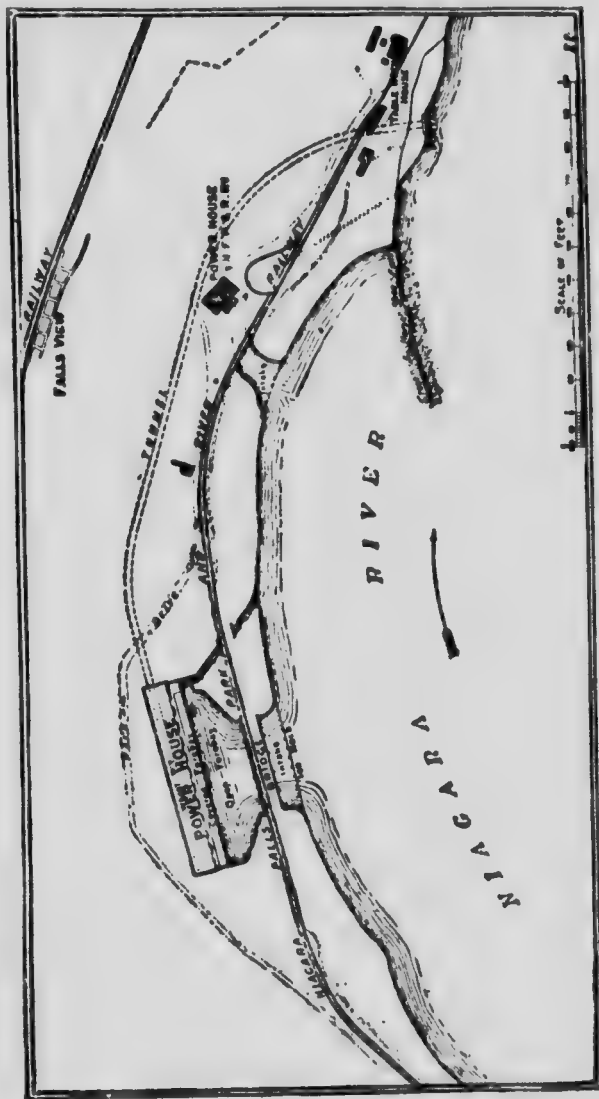


Fig. 503. - Canadian Niagara Power Company: Map showing Power Development in Q. V. N. F. Park 1904.

The results having thus rapidly proved the wisdom of the projectors, steps were soon being taken to utilise the water power in a similar manner on the Canadian side, where the Canadian Niagara Power Company was

formed. The success of the large units on the American side had been so marked that this company adopted a unit of 10,000 H. P. as its standard size, being much larger than had hitherto been designed anywhere else, and planned a power scheme to include ten such units in a single station whose capacity would therefore be 100,000 H. P. A view of this station in the early stages of its equipment, and showing three alternators in



Fig. 504.—Hydro-Electric Station of Canadian Niagara Power Company (under construction).

position, is given in Fig. 504. These alternators are of the internal revolving-field type, and are 10 feet in diameter over all; they generate three-phase current at 12,000 volts, and 25 ω when running at 250 R. P. M.

The position of the power house on the river above the Falls and the general character of the civil engineering works, which had to be undertaken to divert the water of the very rapidly flowing river, are shown in the map given in Fig. 503. In the first place it was necessary to construct at the side of the river a large open forebay in which the water could become to some extent quiescent before flowing into the penstocks. Then, as on the American side, a long tail-race tunnel, whose position is shown in the map, had to be constructed from the site of the

power house to a convenient outlet below the Falls.

A section of the power house, the covered part of the forebay, the wheel pit, and one of the side chambers is given in Fig. 505. The main building is 600 feet long, and 40 feet high to the eaves, the crane girders being 31 feet from the floor. The machinery room which runs the whole length of the building has on one side the eleven large generators immediately over the wheel pit and the turbine governors, and on the other side the switchboard. The covered forebay outside the main building forms a pleasant promenade. The subways under the machinery room floor on the right-hand side of the wheel pit are used for cable runs, whilst the subway on the other side is also for cables and the substructure of the switchboard. The top of one of the penstocks can be seen in the section. These penstocks, each of which carries the whole of the water for one of the main turbines are 122½ inches in diameter, the water at full load passing through them at a speed of 11 feet per second. The turbines are not at the bottom of the pit, partly because of the great depth of water in the pit when all the turbines are running, and also because of the level of high water in the lower river. The turbines are therefore placed 47 feet above the invert of the tunnel, a cross section of which is shown in Fig. 506. The turbines are twin inward-discharge Francis reaction turbines, giving 10,000 shaft H. P. at 250 R. P. M., with a net effective head of 136 feet. The principal dimensions of the tail-race tunnel

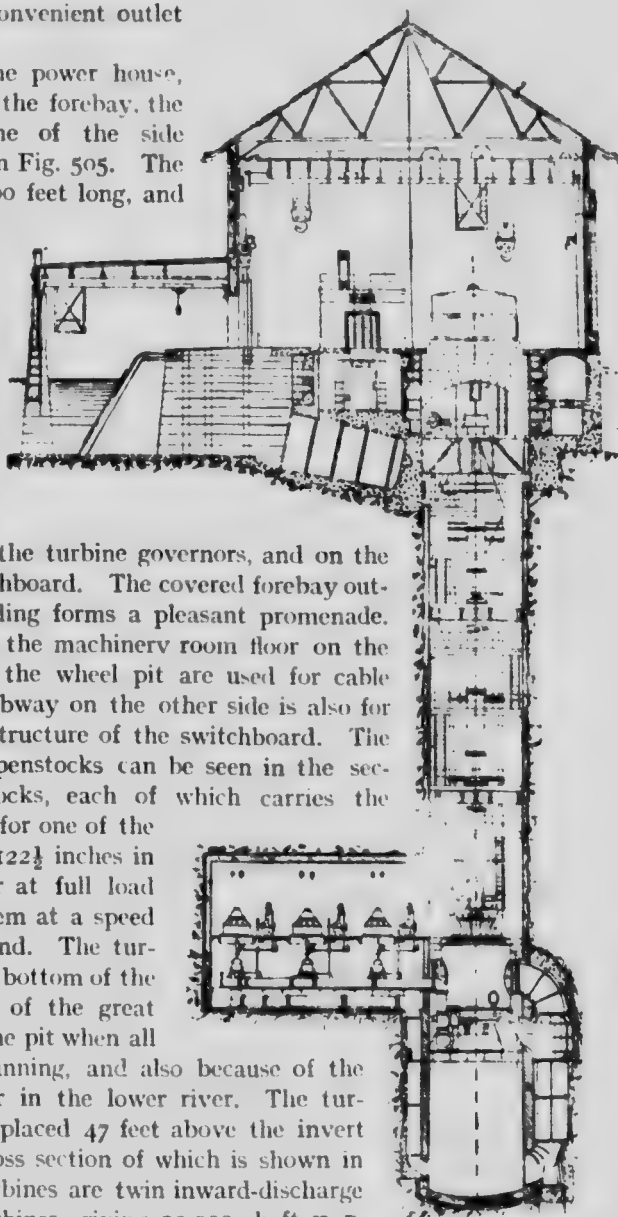


FIG. 505. Canadian Niagara Power Company: Cross-section of Power House and Wheel Pit.

section are given in the figure; it is 2,200 feet long, the greatest dimensions of the cross-section being 25 feet high, by nearly 19 feet wide.

The side chamber shown near the bottom of the wheel pit contains three vertical turbines, each of 330 H. P. and driving a continuous current generator giving 125 volts at 600 R. P. M. The turbines are supplied with water from a separate penstock 36 inches in diameter, and work with a 131-feet head; the tail-race water is discharged into the bottom of the

wheel pit as shown. The continuous current generated is used not only for the excitation of the large alternators, but also for lighting, operating cranes, oil switches, pump motors, and the general work of the station.

There are two other similar chambers at the side of the wheel pit. One of these contains two powerful water pumps; another the oil pump, and an air compressor. The lubrication of these huge vertical shafts was a difficult problem, as might be expected, when it is noted that the weight of the revolving parts

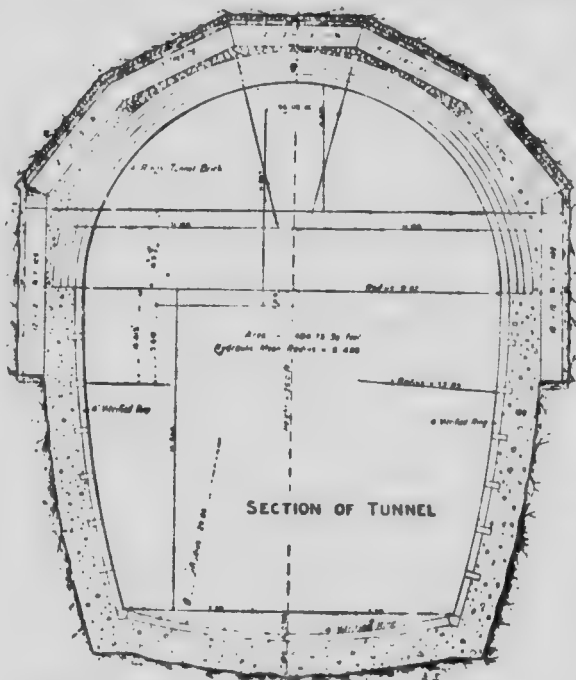


Fig. 506.—Section of the Tail-Race Tunnel of the Canadian Niagara Power Company.

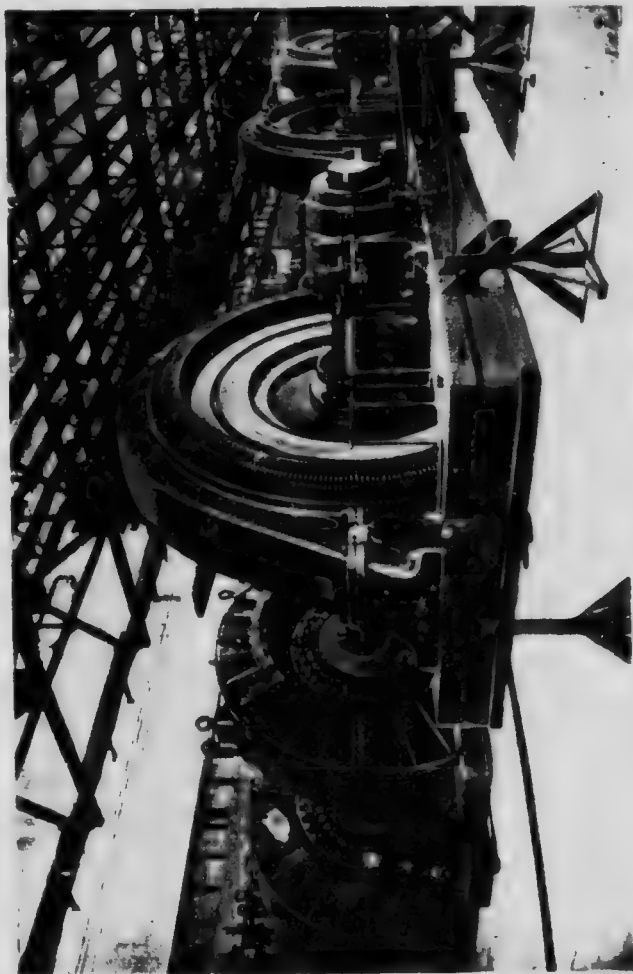
of a big unit is about 243,000 lb.; forced lubrication has therefore to be used. Hence the necessity for the oil pumps in one of the chambers.

In conclusion it may be recorded that the construction work was commenced in September, 1901, and that the first large unit began running before the end of December, 1904.

Meanwhile, on both sides of the river advantage was being taken of the other method of utilising the power of the Falls by conveying the water from the upper river in pipes or canals to the edge of the lower gorge, and passing it thence in penstocks to water turbines placed at the foot of the cliff. In these stations the shafts of the large turbines and generators are horizontal.

On the Canadian side the Ontario Power Company brought the water to the top of the cliff in a steel pipe about a mile long and 18 feet in diameter, laid underground through Victoria Park. A view of the interior of the power house at the foot of the cliff is given in Fig. 507. Each generating set consists of two turbine wheels, each capable of developing 5,000 H. P., driving a single 10,000 H. P. alternator. The first three sets are shown, but the station and the water supply were designed for eighteen sets in all, or a total of 180,000 H. P. The sets subsequently installed are four of 9,000 kilowatts each and five of 9,700 kilowatts, so that the present capacity of the station is well over 100,000 kilowatts.

On the American side the Niagara Falls Hydraulic Power and Manufacturing Company constructed a station to which the water is brought from the upper river by an open canal. In this station the shafts are horizontal, and at first, in 1860, the sets were comparatively small, averaging about 1,250 H. P. each. Later, the station was enlarged, and the success of large units being assured, the



smaller sets were replaced by 10,000 H. P. sets running at 300 R. P. M., each set consisting of a single turbine wheel driving two 5,000 H. P. alternators on the same shaft. The water is brought down to the turbines from the top of the cliff by penstocks 9 feet in diameter, the minimum "head" being 200 feet.

Other large stations have since been erected, but mention need only be made, in conclusion, of the station of the Electrical Development Company on the Canadian side, placed above the Falls with its turbines in a wheel pit 138 feet deep. Each turbine is capable of developing 13,000 H. P. at three-quarter-gate opening, and is mounted at the bottom of a hollow shaft 115 feet long, supported by three intermediate bearings. A section of one of these turbines will be found on page 487. It drives an 8,500 K. W. alternator generating three-phase currents at 12,000 volts and 25 ω . There are seven of these sets and therefore the capacity of the station is about 60,000 kilowatts. The tail races, of which at the power house there are two, one on either side of the line of turbines, merge into a single tunnel which is driven under the bed of the upper river, and, at a distance of about 2,000 feet from the power house, discharges its water from the face of the cliff over which the Falls themselves pass, and behind the curtain formed by the celebrated Horseshoe Falls.

Stations utilising High Falls.—Niagara is an example of a comparatively moderate fall which derives its importance from the fact that it is interposed in the course of a river which is carrying the water collected from an enormous drainage area. The district itself is not mountainous in the ordinary acceptation of the word, and the average fall per mile spread over the greater length of the waterway is not excessive. Similar examples, some of which may in the future play a still greater part in industrial development occur in other parts of the world, the most notable of which as yet discovered is probably the Victoria Falls on the Zambesi, in Central Africa, where the sudden vertical fall is about three times that at Niagara, and the water passing over is collected from probably a larger drainage area. A still higher fall occurs at Kaieteur, on the River Potaro, in British Guiana, where there is a drop of over 740 feet. The quantity of water available and the drainage area are large, but accurate statistics are not available.

In mountainous districts the conditions are different. There great quantities of water fall down a considerable vertical height in the course of a few miles of direct horizontal travel. The water, however, is usually split up into a number of streams, no one of which carries a quantity of water which can be compared to that carried by the Niagara or the Zambesi rivers. Moreover the greater part of the vertical fall is not taken abruptly in a single leap, but in a series of cataracts or jumps, no one of which by itself would be capable of generating a large quantity of mechanical or electrical

power. The total water power is thus split up over a considerable area, and if it be desired to utilise it on a large scale, engineering works of varying magnitude and costliness, depending on the physical features of the country, have to be undertaken to concentrate the water with sufficient "head" at a single spot where large turbine-driven modern generators can be installed. These works consist of dams placed across the mouths of valleys to impound the water coming down, of pipes or open conduits or flumes carried along the sides of the mountains, of tunnels through the mountains by which the water is transferred to a neighbouring valley, and of other engineering devices all having the one object of concentrating a sufficient quantity of water at a sufficient height above a position convenient for the erection of a power house to which the water is finally conveyed by vertical or nearly vertical penstocks from the high level where it has been collected to the power house below. The tail race as a rule presents no difficulty, and, in fact, it is not uncommon for the water from one power house to be again collected and made available for the production of additional power at another power house at a lower level.

It would be beyond the scope of this book to describe in detail the various devices for collecting the water and concentrating its energy at a convenient point, but the final stages of conveying the water to the power house may claim a little attention. Fig. 508 gives a view of the power house at Rio das Lages, in which the sloping penstocks bringing the water down from the higher level to the power house are clearly discernible. The station is in the mountainous district, fifty-six miles from Rio de Janeiro, in Brazil, and is intended to supply electric energy to that city, to which it is transmitted from the power station by three-phase currents at 80,000 volts pressure. It is estimated that 120,000 H. P. is available in the driest season.

The penstocks seen in the figure are six 36-inch iron pipes, each about 1,900 feet long, leading from receivers at the top of the slope, which are 900 feet above the level of the power station. The large reservoir which stores the water is at a still higher level about a mile farther away, and when it is full the total head available at the power house is 1,030 feet, which represents a pressure of 445 lb. per square inch, this pressure being obtained by a horizontal travel of about one and a half miles from the reservoir which collects the water from the drainage area. Each of the penstocks supplies water to a turbine which at full gate and head is capable of developing 9,000 H. P. Each turbine is directly coupled to a three-phase alternator which generates 6,000-volt currents at 50 ω . For transmission the voltage is stepped up to 80,000 volts by suitable transformers. As the demand increases additional plant will be installed and will be supplied with water by additional penstocks.

As a second example of a high-pressure water-power station, Fig. 509 gives an external view of a hydro-electric station in the River Löntsch

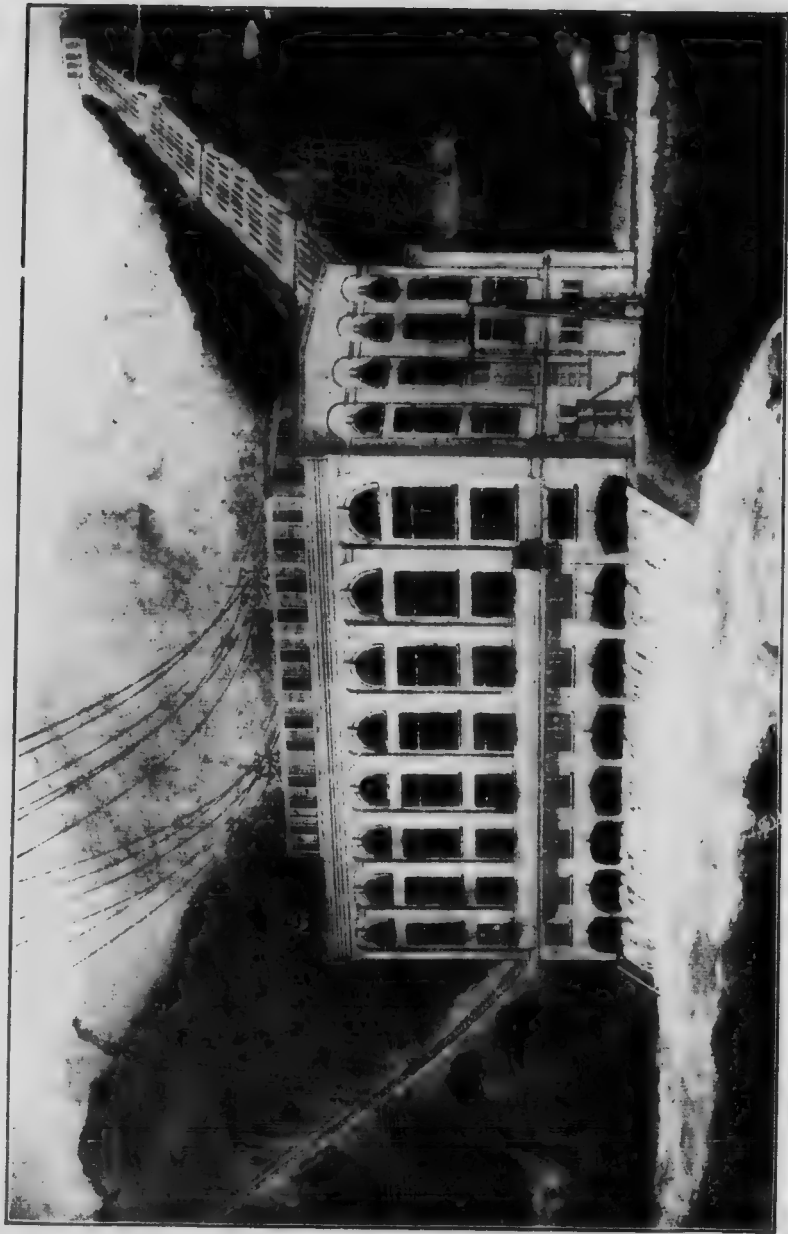


Fig. 508.—High "Head" Hydro-Electric Station at Rio das Lages (Brazil), showing Penstocks.

equipped in the mountainous district in the north of Switzerland by Messrs. Brown, Boveri and Co., Limited. The water is drawn from the



Fig. 509.—High "Head" Hydro-Electric Station in Switzerland.

Klonthalersee, a mountain lake, the water from which is brought through a tunnel through the solid rock of the Wiggis mountain for over two and a half miles to the top of the slope seen in the

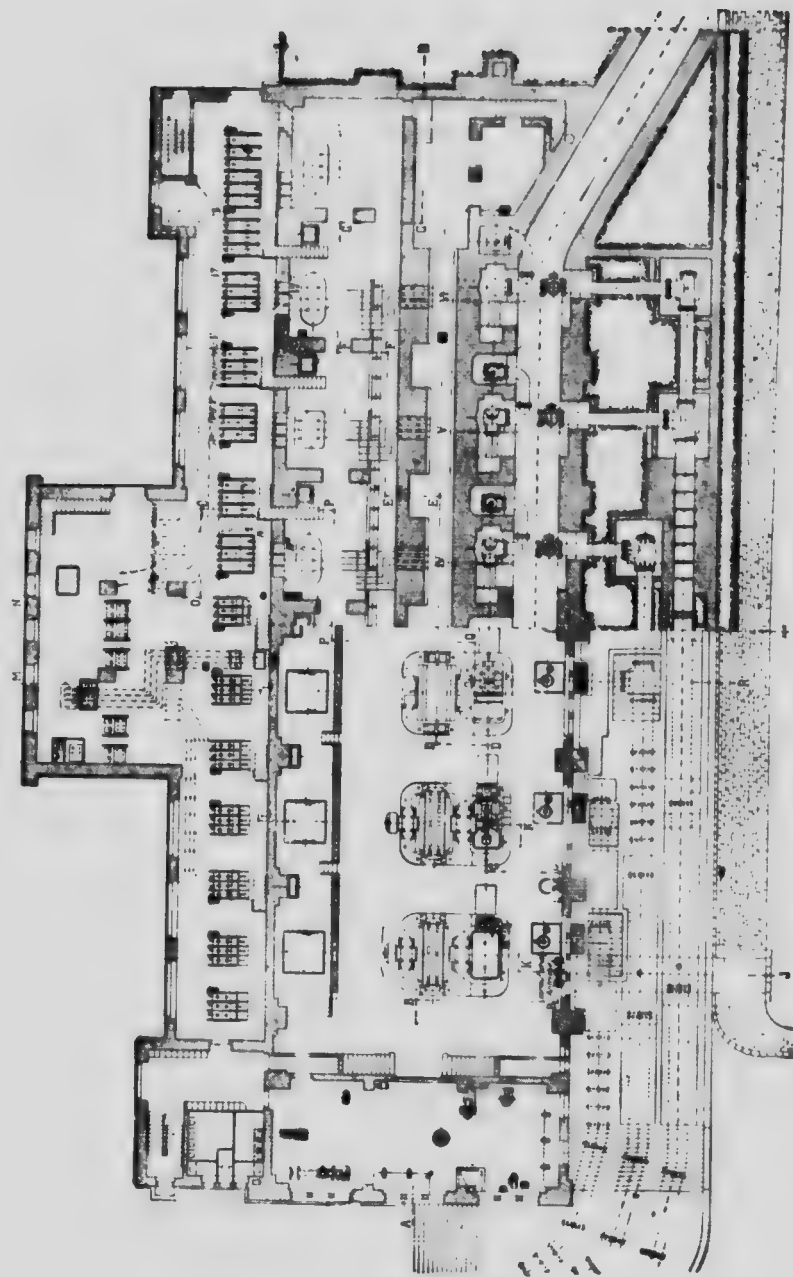


Fig. 510.—Plans of High "Head" Hydro-Electric Station in Switzerland.

picture. Here the conduit formed by the tunnel makes a watertight concrete joint with the ends of the three welded steel pipes which are to carry the water to the power house at the foot of the cliff. These high-pressure pipes are about 1,400 yards long, and are very heavily anchored in section lengths to the rock. The diameter varies in the different sections from 53 inches at the top of the slope to 41.4 inches at the bottom. The vertical fall from the top of the pipes to the power house is 1,070 feet and the working "head" at the turbines is about 1,000 feet. The penstock pipes are brought round the front of the power house, so that if any of them burst the water would not flood the power house, but flow away harmlessly with the tail race down the river.

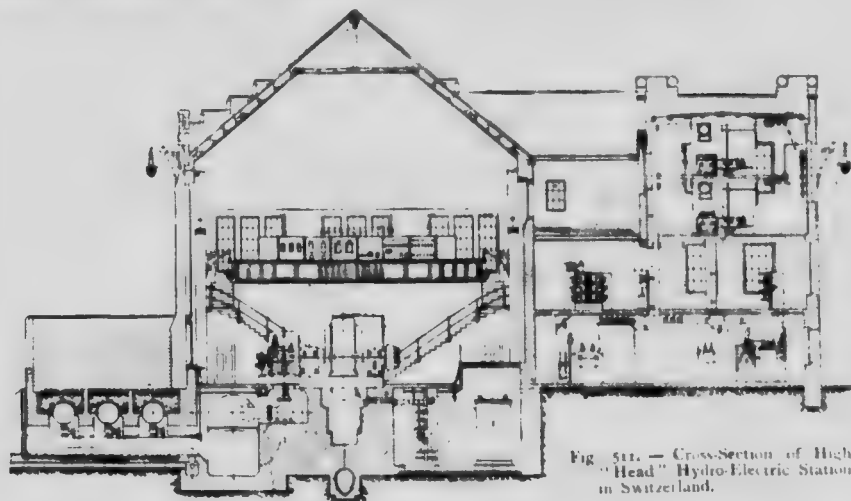


Fig. 511. — Cross-Section of High "Head" Hydro-Electric Station in Switzerland.

A plan of the station is given in Fig. 510, one half of which is drawn as the plan of a horizontal section above the generating sets, and the other half as a horizontal section below the machines, but above the horizontal lengths of the incoming pressure water pipes from the penstocks. A vertical cross-section of the building looking towards the switchboard gallery, which is at the end nearest the penstocks, is given in Fig. 511. There are six generating sets on the floor of the station arranged in a single row; they are grouped in pairs, each pair being supplied with water from one penstock. The course of the supply pipes and of the common tail race for the six turbines can be traced. Some details of these particular turbines, which are impulse turbines, are given elsewhere (*see* pages 257 and 486). They each develop 6,000 H. P. when running at 375 R. P. M. The alternators have also been described (*see* Figs. 257 and 258, pages 258 and 259), and it need only be re-stated here that the output of each is 5,250 K. W. A. at a

power factor of 0.8 on full load. The current is generated at 8,000 volt which is raised for transmission to 27,000 volts by one group of transformers or to 48,500 volts by another group. These transformers it will be noticed are contained in chambers below the level of the machinery floor; there is one transformer to each machine.

As a final example of a "high-fall" station reference may be made to the largest hydro-electric generating station in Great Britain, which, however, is not a public supply station, but may be briefly described here as being of special interest to our readers.

The works are remarkable from several points of view. In the first place they are not near any industrial centre, nor is any transmission scheme connected with them. All the power generated—over 21,000 kilowatts—is utilised on the spot for the electrical production of aluminium. The power station is at Kinlochleven, some sixty miles from Glasgow, and not far from the head of Loch Leven, which is freely accessible from the open sea. The whole of the works which were ready for running in 1909, belong to the British Aluminium Company, Ltd.

The reservoir from which the water is drawn is about 1,000 feet above the level of the power station. This reservoir has been formed by throwing a dam 3,112 feet long and 86 feet high at its highest point across the valley of the River Blackwater, thus impounding the water falling on a catchment area of about 55 square miles. When full, the water surface is $7\frac{1}{2}$ miles long and $\frac{1}{2}$ mile wide.

The water is conveyed to the power house first by a concrete conduit 8 feet wide and $3\frac{1}{2}$ miles long, which follows the winding of the valley of the Leven and only drops 17 feet in its whole length, terminating in a penstock chamber from which pipe lines start. These pipe lines are six in number, and are made of welded steel pipe having an internal diameter of 30 inches. Each line is $1\frac{1}{4}$ mile long and discharges its water 935 feet below the weir crest of the penstock chamber. The appearance of these lines as they pass down the hillside from the penstock chamber is shown in Fig. 512. Many interesting problems had to be solved in laying the pipes, but it is impossible to refer to them here. The water delivered to the turbines has, it will be noted, a net static "head" of 935 feet or 406 lb. per square inch, but about 24 feet "head" is lost in friction in the pipes. The tail-race is a tunnel under the power house, which discharges in an open conduit about 700 feet long to an outfall into the River Leven.

The turbines used are impulse turbines (Pelton wheels), the wheels being 8 feet in diameter and similar to the turbine illustrated in Figs. 256 and 404, but with the two nozzles lower down and closer together, directing the water underneath the shaft, which is horizontal. There are nine large turbines, each of 3,200 B. H. P., and two small turbines of 930 B. H. P. each;

the large sets run at 300 to 330 R. P. M. and the small sets at 400 to 440 R. P. M.

The station is also remarkable amongst large modern stations, inasmuch as only continuous currents are generated, this being due to the fact that such currents are required for the production of aluminium, and that there is no necessity for high-voltage A. C. currents for long-distance transmission.



Fig. 512 - Pipe Lines of the Kinlochleven Hydro-Electric Station.

Each large turbine drives directly two Dick, Kerr c. c. dynamos, with a total maximum output of 2,200 kilowatts at 275 volts. The interior of the power station, including most of the large sets, is shown in Fig. 513. The Pelton wheels are on the left-hand end of each set, and the two c. c. dynamos coupled on its shaft can be easily distinguished. The maximum current from each set, it will be noticed, is 8,000 amperes, and the total maximum current from the nine sets is, therefore, 72,000 amperes. These enormous currents are entirely used in the manufacture of aluminium. In the small turbines each wheel also drives two Dick, Kerr dynamos; one of

these in each set has an output of 550 kilowatts at 275 volts, and is used for lighting the factories and the village, for driving motors, and for exciting the large dynamos, when running, at a low voltage. The other dynamo

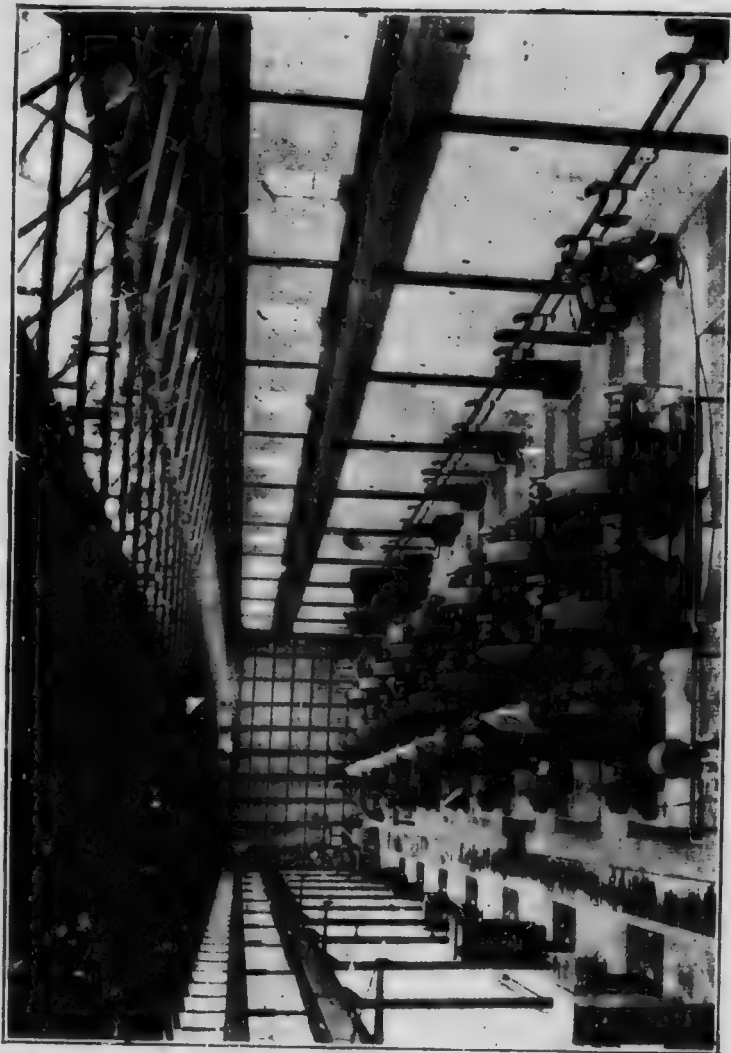


Fig. 513.—Interior of the Kinlochleven Hydro-Electric Station.

has a maximum output of 94 kilowatts at 550 volts, used for traction and crane work, and also for supplying current to outside arc lamps.

It is interesting to note that the distribution circuits and all their connections in this unique installation are made by bare aluminium conductors

in the form of strips carried on porcelain insulators. The total length of feeders and distributors is about nine miles.

Stations utilising Moderate and Low Falls. An interesting example of a hydro-electric public supply station with a moderate



Fig. 514.—The Vizzola Hydro Electric Station on the River Ticino (Italy).

"head," is the Vizzola power station on the River Ticino in northern Italy, some 20 miles from Milan. An external view of the buildings is given in Fig. 514. The lower building is the power house, and the upper building is at the end of the forebay, its function being to regulate

the supply to the penstocks which convey the water to the power house. The forebay with the weir on the left is shown in Fig. 515. This forebay is about 2,000 feet long, and receives its water from a canal, the intake of which is about $3\frac{1}{2}$ miles from the forebay. The

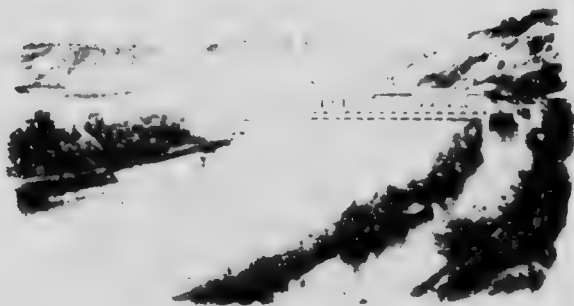


Fig. 515.—Forebay and Weir of the Vizzola Hydro-Electric Station.

sluice gates at the end of the forebay can pass 200 cubic metres (nearly 200 tons) of water per second.

The interior of the power house is shown in Fig. 516: the huge bent pipes which are so prominent in the picture carry the water from the lower ends of the steel penstocks into the turbine, the available "head" varying

from 80 feet to 95 feet. The shafts of the turbines are horizontal, and each carries two water wheels of the radial inward-flow reaction type; each wheel can develop 1,000 H. P. when running at 187 R. P. M. The alternators coupled to the turbine shaft have a normal output of 1,650 kilowatts, the current generated being three phase, at 11,000 volts, and 50 ω . There are ten of these alternators and three 145-kilowatt exciters.

The interior of a moderate "head" hydro-electric power station with vertical shaft alternators is shown in Fig. 517. It is a station at Schaghticoke, in the State of New York, erected by the Schenectady Power Company, and illus-

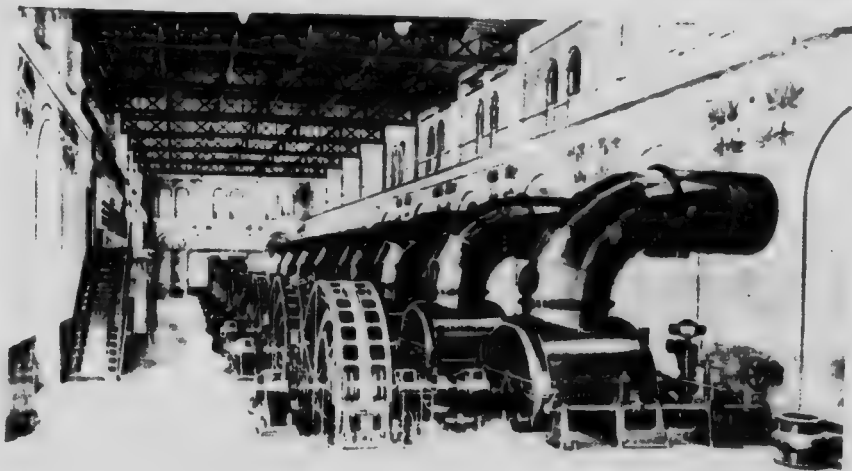


Fig. 516.—Interior of the Vizzola Hydro-Electric Station.

trates American practice, the machines being similar to the slow-speed alternator described on page 227, and built by the General Electric Company of America. The station is about 20 miles from Schenectady, and is fed with water from the River Hoosic by a canal and penstock of about a mile in total length, the river being dammed at the intake so as to give a water-power estimated under ordinary working conditions at over 50,000,000 kilowatt-hours per year. The average working "head" is 145 feet. Each of the four alternators in Fig. 517 has an output of 4,000 kilowatts at 40 ω and 4,400 volts when running at 300 R. P. M.; the currents are three phase. The exciters are driven by two small turbines of 250 H. P. each with horizontal shafts running at 600 R. P. M.

As an illustration of the modifications which may be adopted in designing a hydro-electric generating station, Fig. 518 shows partly in section an hydro-electric generating station at the Snoqualmie Falls in the State

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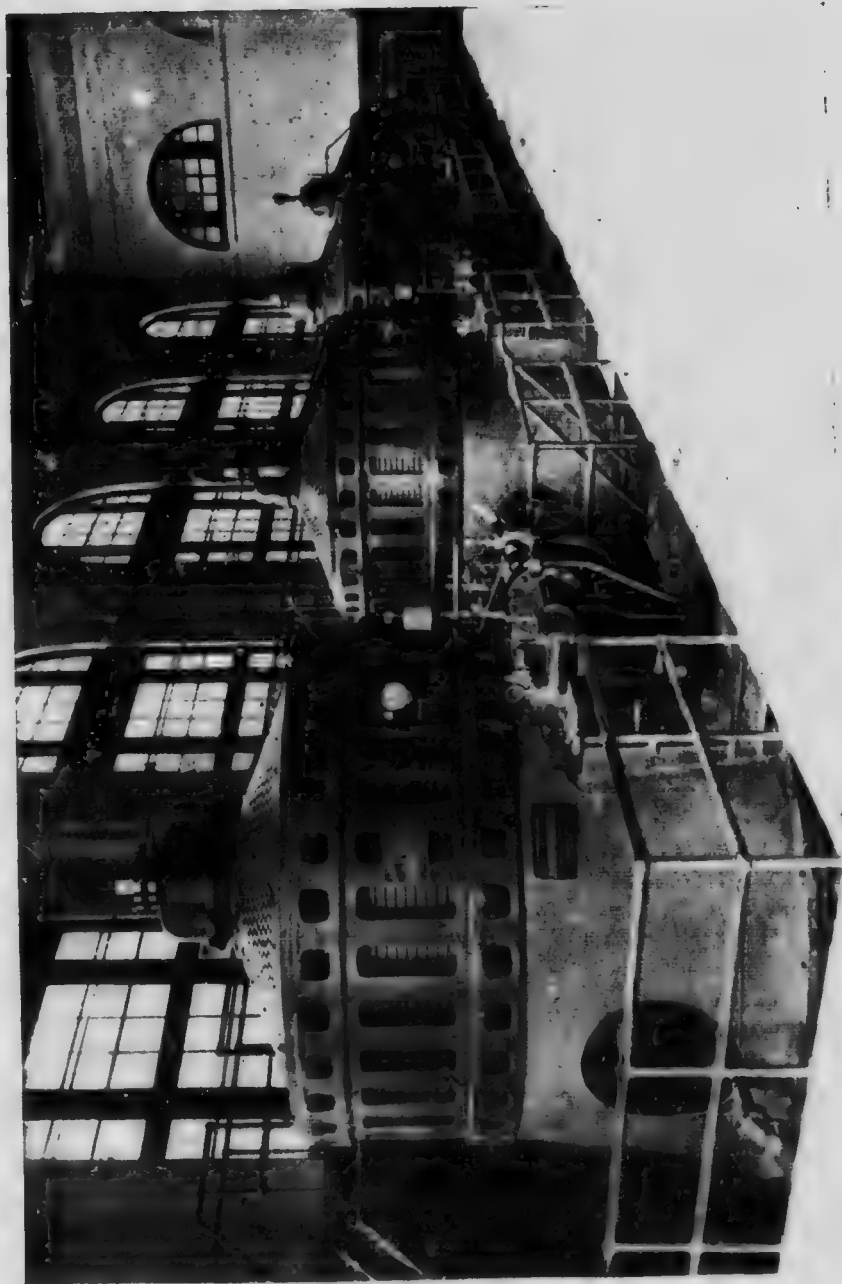


Fig. 547.—Hydro-Electric Station, B. & O. R. Co., New York City.

of Washington, and about 31 miles from Seattle. The falls are 270 feet high, and the river has a watershed of 400 square miles. The minimum



Fig. 513. Underground Hy. Elec. Station at Snoqualmie Falls, Rocky Mountains

power available was estimated at 100,000 h. p. The remarkable feature is that the actual generating station shown is a room 200 feet long, 40 feet wide, and 30 feet high, cut in the solid rock at the bottom of a shaft

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Fig. 513. - Underground Hydro-Electric Station at Snoqualmie Falls (Rocky Mountains)



Fig. 519. - Low "Head" Hydro-Electric Generating Station at Lenz, Switzerland.

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260 feet deep, and having a section of 25 feet by 10 feet. The shaft is about 200 feet back from the edge of the Falls, and contains the penstock for conveying the water to the generating room, and also a passenger lift. The first penstock erected was $7\frac{1}{2}$ feet in diameter, but space was provided

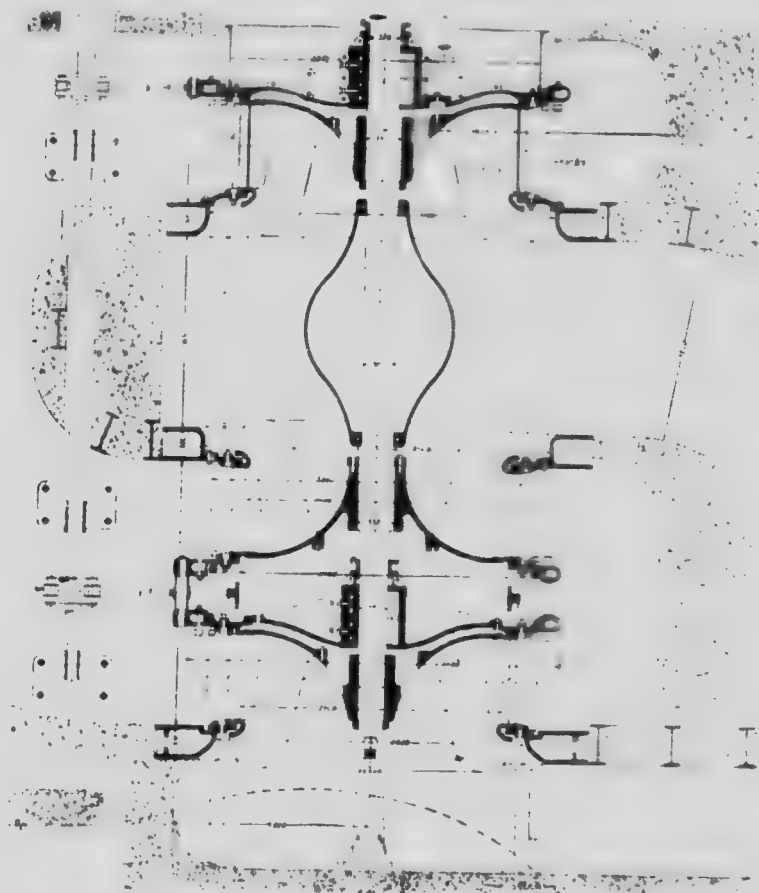


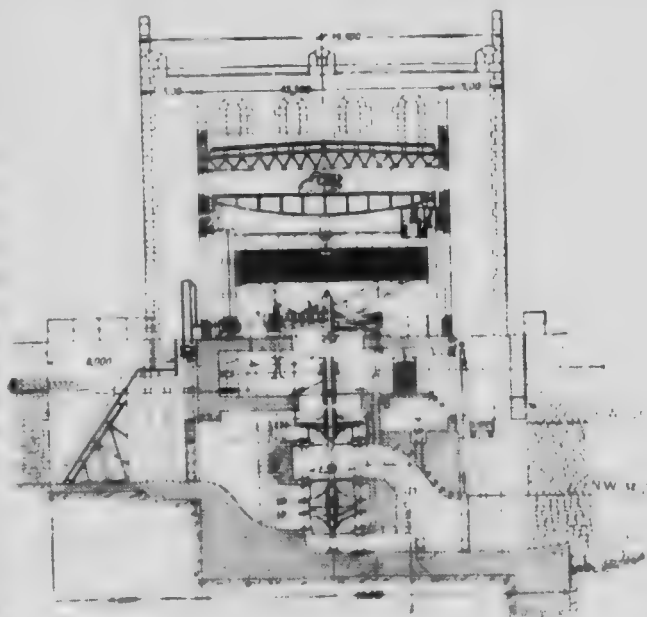
Fig. 520.—Vertical Section of Low "Head" Turbines at Bernau

for an additional penstock if and when required. The intake at the top of the penstock is carefully protected so that driftwood or other solid materials shall not be allowed to enter the penstock. In the room where the penstock was continued horizontally 10 feet from the floor to supply pressure water at 120 lb. per square inch to four large turbines and one smaller one. The turbines have vertical shafts, and the four large ones, each running at 300 R. P. M., drive a 1,500-kilowatt alternator, while the smaller

...drives two 75-kilowatt exciters. The tail race is a tunnel below the level of the chamber, excavated in the rock so as to discharge the water at the foot of the Falls. The alternate current generated is three phase at 60 cycles which, generated at 2,000 volts, is stepped up by transformers to 110,000 volts for transmission to Seattle, Tacoma, and more distant places.

As an example of a European hydro-electric station with a low "head" of water Fig. 519 shows the interior of the electric generating station at Beznau, on the river Aare, in Switzerland, close to its junction with the Rhine. The

necessary fall obtained by cutting a canal across the neck of a bend in the river, the water of the river being held back by a weir just below the intake of the canal, which is only about 1,300 yards long. The turbine house is built across the outlet of the canal, the water of which flows through it to



1. *Verdun* (1916) 100,000 killed

[illegible]

the time, money, and effort involved in the process of developing a new product, the firm must be able to identify and exploit market opportunities that are profitable and sustainable.

and two for the turbines driving the continuous current exciters. In Fig. 519 the two latter are seen in the foreground, and the eleven large

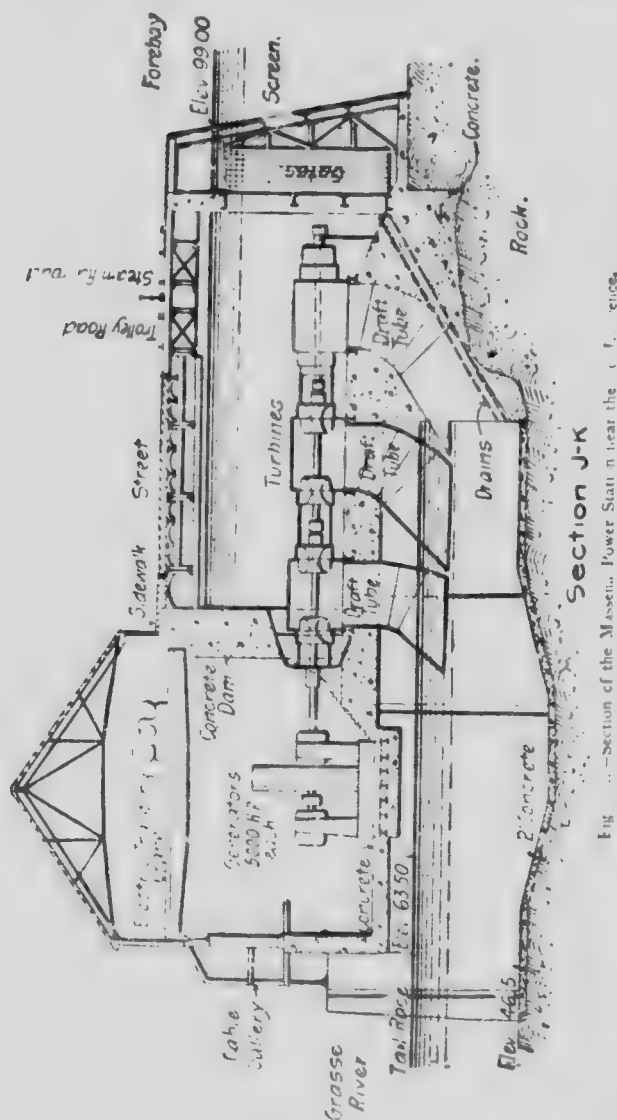


Fig. 519 - Section of the Massena Power Station near the Grasse River.

alternators farth back. On each shaft there are three turbine wheels, the upper one of which only can effectively operate when the river is in flood and the available fall small, but when the river is low the whole three wheels come into operation. These wheels arranged on the shaft are shown in the dimensioned sketch in Fig. 520, in which the dimensions are in millimetres. The alternators run at 60½ R. P. M., and can each absorb 1,200 H. P. producing three-phase currents at 50 Ω and 8,000 volts. The position of the turbines and the generators in the station, and some of the details of the passage of the water from the higher to the lower levels, are shown in Fig. 521, which is a vertical cross-

lowatts when running at 1,500 R. P. M., so that a considerable quantity power can be produced otherwise when the water power is insufficient. The switch gallery is at the end of the station close to the exciting dynamos seen in Fig. 519. These dynamos can absorb 400 H. P. each and generate continuous currents at 150 volts, when running at 85 R. P. M. They are placed at the end of the house where the fall is greatest.

For very low falls, where great quantities of water have to be used to obtain large amount of power, penstock's and even the outer casings of the turbines are sometimes dispensed with. The wheels of the latter can be placed uncovered in the lowest possible position to receive the water coming from the higher level, the necessary arrangements being made by suitable draught tubes

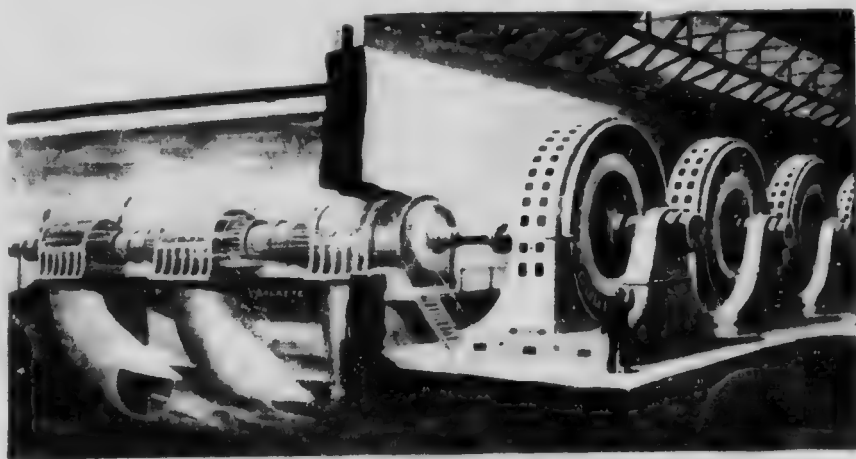


FIG. 521.—The turbine Chamber and Generator Room at Massena

or tunnels to lead away the water after it has passed through the wheels. An excellent example of this is shown diagrammatically in Fig. 522, which is a section of the power station erected on the banks of the River Grasse, at Massena, on the United States side of the St. Lawrence River. The Grasse is an affluent of the St. Lawrence, and is used only to receive the tail-race water, the power water being brought from the St. Lawrence by a canal about three miles long, 200 feet wide, and 18 feet deep. The Massena end of the canal is at the forebay shown in Fig. 522 from which the water flows quietly into the turbine chamber at the same level through the necessary screen and gates. It may be noticed that there is a street over this turbine chamber. The turbine wheels which are of the radial inward flow reaction type are placed at the bottom of this flooded chamber, there being three per shaft, developing altogether 5,000 H. P., on each shaft. A better view of the arrangement can perhaps be gathered from Fig. 523, which shows the turbine chamber and the dynamo room in perspective.

Each turbine shaft passes through the dividing concrete wall into the dynamo room, and carries at its other end the rotor of a revolving-field

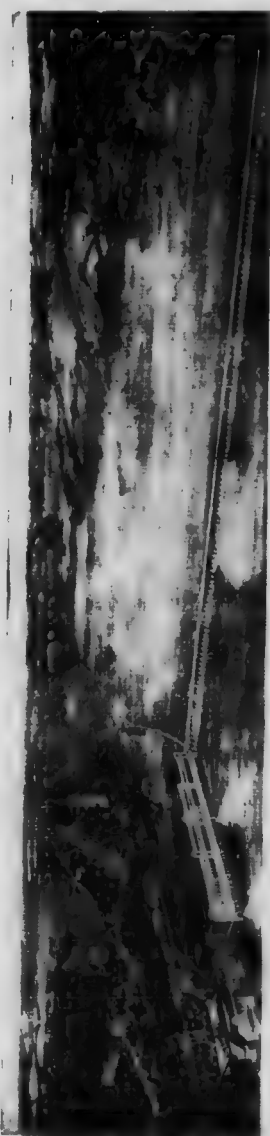


Fig. 524. View of the Keokuk Mississippi River Station and Dam.

Westinghouse 5,000-h. p. alternator. The size of the generator is therefore the same as in the first two power houses at Niagara, and it then becomes interesting to note that the horizontal shaft at Massena is about 80 feet long, compared with the 150 feet vertical shaft, but that owing to the lower "head" and the much greater quantity of water to be handled the Massena shaft carries six turbine wheels as compared with the two carried on the Niagara shaft. The difference of levels between the water in the forebay and the water in the tail race as shown in Fig. 522, is 35.5 feet, but as the bed of the river is about 17 feet lower, a working "head" of about 45 feet can be obtained.

The power house, which is built on the solid rock, is about 300 feet long, 150 feet wide, including the turbine chamber, and 85 feet high. The station was planned for an ultimate capacity of 75,000 h. p., and the first section of the plant was ready for running early in 1901. It was the first portion of the equipment, which was intended to consist of six sets of 5,000 h. p. Westinghouse alternators, but the development of the load as the requirements of the company's customers became better defined caused the original plans to be modified. The power house now contains three Westinghouse 3,750-kilowatt alternators and six Westinghouse and four Bullock 2,200-kilowatt C. C. generators. The present capacity of its plant is therefore about 33,000 kilowatts, and there is ample power for further additions.

This section may appropriately conclude with a description of what is probably one of the largest schemes yet designed for utilising a low "head" of water. A good idea of the main outlines of this scheme, which is designed to utilise some of the water power of the Mississippi, can be obtained from Fig. 524, which shows the electric power station and the necessary dam erected across

the river between Hamilton, Illinois, and Keokuk, Iowa, the power station being on the Keokuk side. The long dam, transverse to the course of the river, and which forms a spillway for the surplus water, has been erected at the foot of the Des Moines Rapids, which, although they did not have a great fall, were impassable for navigation. Before the building of the dam the rapids had to be passed by means of a canal, and locks, the upkeep of which cost £8,000 per year. By the construction of the dam which is 4,278 feet (0.8 mile) long, the rapids have been submerged, and not less than 6 feet of water has been secured for 65 miles on the upper side of the dam. As the total "head" obtained at Keokuk varies from 40 feet to 14 feet only it will be obvious that the average natural fall of the river is very slight. The spillway level is 32 feet above the river bed.

The power house which is 1,790 feet long, is built (Fig. 524) at right angles to the dam on the down-stream side. A plan and elevation are given in Fig. 525, which, with Fig. 524, is taken from the *Practical Engineer*. The right-hand half of the elevation shows the appearance as seen from the up-stream side, and the other half the appearance as seen from the down-stream side. The smallness of the "head" obtained is indicated in the elevation, but is shown in greater detail in Fig. 526, which gives a cross-section through the middle of the power house and has marked on it the high- and low-water levels on both sides. The structure is divided longitudinally by a wall with chambers into a screen room and a generator room, the latter being 48 feet 6 inches wide, with its floor 5 feet above high-water level. The water passes to the screen through submerged arches, but to guard more effectually against floating ice, a long ice fender, 2,800 feet long, has been

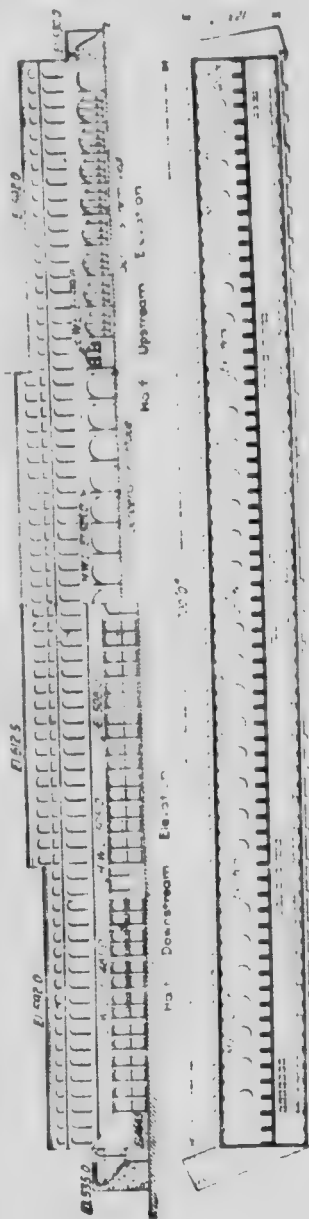
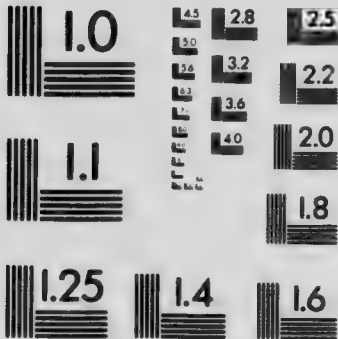


Fig. 524. Plan and Elevation of Keokuk Hydro-Electric Station.



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built up stream from the junction of the dam and the power house. This fender is of concrete, and has submerged openings for the passage of the water. It serves to direct the floating ice towards the spillway, and away from the power house. The waterways under the power house are clearly shown in Fig. 526, but the position of the wheel and the generator is only indicated by a centre line. The preceding pages, in which low "head" wheels have been described will enable the reader to fill in the details.

A reference to Fig. 525 will show that the generator room is planned for 30 units. Each of these is intended to have an output of 7,500 kilowatts,

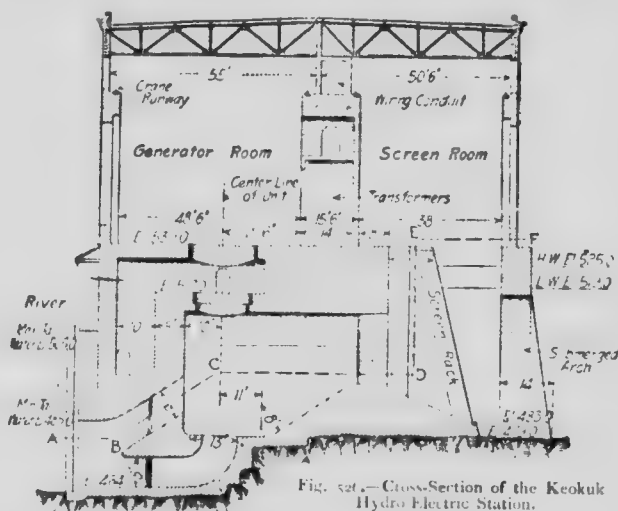


Fig. 526.—Cross-Section of the Keokuk Hydro Electric Station.

so that the total electric power generated will be 225,000 kilowatts. The radius of transmission will be about 200 miles, which will reach many important cities and districts, including St. Louis, which is 170 miles distant.

It may be noted that the navigation of the river is provided for by a lock, 400 ft. long, and 110 feet wide, which can be seen in Fig. 524 below the power house.

V.—SWITCHBOARDS AND SWITCHING

By far the most important part of a modern electric generating station is the part devoted to what is known as the switchboard. This represents, as it were, the nervous centre of the whole system, and any serious accident happening at this point throws the system out of gear throughout its whole extent. It is therefore only to be expected that very great attention, skill, and inventive ingenuity should have been expended on the design and arrangement of the apparatus, and it is apparent that it is particularly necessary, so far as is humanly possible, to guard against every adverse contingency.

The objects of the switchboard and its accessories are twofold. In the first place it is intended for the control of the generating plant and the collection of the current for distribution to the various consuming

points, and in the second place it has to control the flow of the current, both in magnitude and in pressure, to the various distributors and feeders.

The first of these objects necessitates the provision of apparatus for altering the voltage at the terminals of the various generators. This can be accomplished most readily by altering the current in the field-magnet circuits either by introducing resistances into those circuits or, where it is possible, by introducing resistances into the field-magnet circuits of the exciters. It is also necessary for the control of the generators that apparatus should be provided for throwing each generator into or out of circuit as may be necessary. This, as will appear in the sequel, is accomplished by means of special switches and equalising busbars with the addition, in the case of A. C. generators, of synchronising devices.

The second object of the switchboard, viz. the direction of current to, and the control of the voltage and current in, the distributors and feeders is accomplished by means of apparatus which either alters the conditions at the switchboard itself or alters the conditions at the distant point by means of boosters, special feeders or sub-stations, and transformers.

Incidental to, and, indeed, necessary for the accomplishment of, both these objects, are the various instruments for measuring current, voltage, power, frequency, etc., and these usually form a very prominent feature on the switchboard. The details of their design and construction are dealt with in other parts of the book; only their application to switchboard purposes will be referred to here.

Having thus summarised the main objects of the switchboard, it may be well to point out a few of the essential conditions which must be observed in its design, and which may be succinctly stated as follows:—

1. The board should be constructed of incombustible materials, so that it is practically impossible to burn it down. It is, therefore, essential that rubber insulation should not be employed, for india-rubber is very combustible.
2. It is essential that the board should be so designed from the point of view of safety that no risk, electrical or otherwise, should be incurred by the attendants either in the ordinary working of the board or even under abnormal circumstances.
3. The conductors carrying heavy currents should be so designed that there is no undue heating at any point. This means that the conductors should be of ample cross-section, have good radiating surfaces, and be so placed as to cool readily.
4. The design should be simple; by which is meant that the purpose of every part should be apparent to a trained attendant without consulting diagrams. All possible wrong methods of working should be prevented by the interlocking of the operating switches or levers.

5. The working parts should be accessible for cleaning with perfect safety to the cleaners.

Classification of Switchboards.—In the almost infinite variety of conditions under which switchboards have to be designed it is not easy to find a comprehensive system of classification and, in fact, as has been found to be the case in other directions in this book, cross-classification is possible and often desirable. The various types of switchboards can be divided either according to the general character of the currents and potentials which they have to handle, or according to the general principle adopted for their construction. From the first point of view the classification for switchboards in large generating stations would be conveniently set forth as follows :—

- (a) High-pressure switchboards.
- (b) Heavy-current switchboards on which the pressure is usually low or moderate.

A subdivision in both types, but more especially in type (a), would be between C. C. and A. C. boards.

Another method of classification, in which the basis is the general design of the board, would lead one to classify the various types as :—

- (i.) Those in which the switching arrangements are on the board, and are operated directly.
- (ii.) Remote control boards in which the actual switches in the circuits operated upon are at a part of the station remote from the board itself, at which the operator stands.

There is also here a possibility of cross classification according as to whether the whole of the apparatus is collected upon a single board, being grouped together as seems best to the designer, or as to whether the board is constructed by the grouping of separate special panels, i.e. generator panels, distributor panels, feeder panels, battery panels, etc.

Directly Operated Boards.—An example of the directly operated non-panel type of board, at one time very widely used and still found useful for special cases, is shown in Fig. 527, which depicts a board designed and manufactured by Messrs. Spagnoletti, Limited, of London. The board is designed to control two continuous current generators supplying current at 480 volts across the outers of a three-wire distributing system. For the purposes of such a system, as explained elsewhere, there is a split battery with balancers and boosters. The feeders are to supply current at 240 volts to either side of the distributing system. A skeleton diagram of the connections of the board is given in Fig. 528, and by comparing the two figures, the details of the operation of the board can be realised.

The outermost sections of the board left and right deal respectively with the — and + sides of the system. The lower part of the left-hand

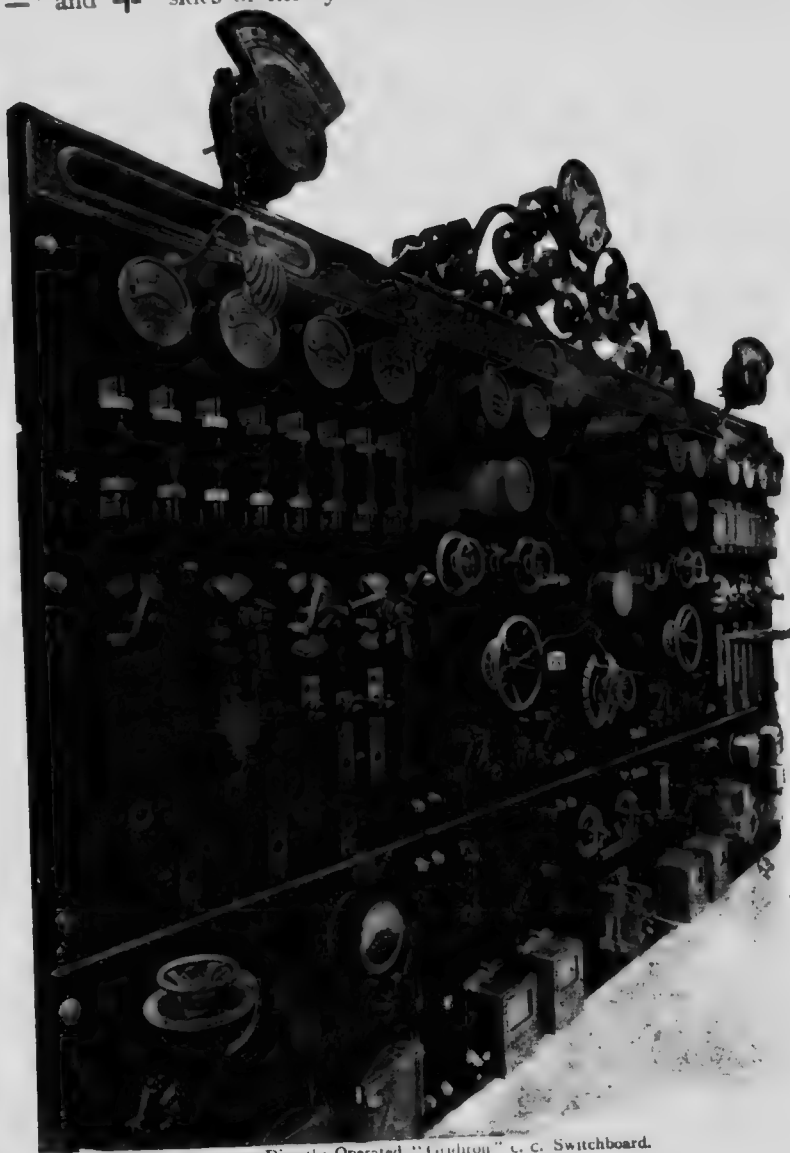


Fig. 527.—Directly Operated "Gridiron" C. C. Switchboard.

section carries the single-pole main switches *s* and fuses *F* (Fig. 528) of the two generators, together with an ampere-hour meter *G* and an ammeter *A* for

each, bringing the current of the two generators to the second and sixth vertical bars seen above. The fourth vertical bar receives current from the battery. On the sections at the other end the $+$ leads of the generators pass through single-pole circuit breakers B to the corresponding vertical bars there, and the lower part of that section carries the shunt regulators and two voltmeters and voltmeter switches, none of which are shown in Fig. 528.

Behind the vertical strips are horizontal busbars on both sections,

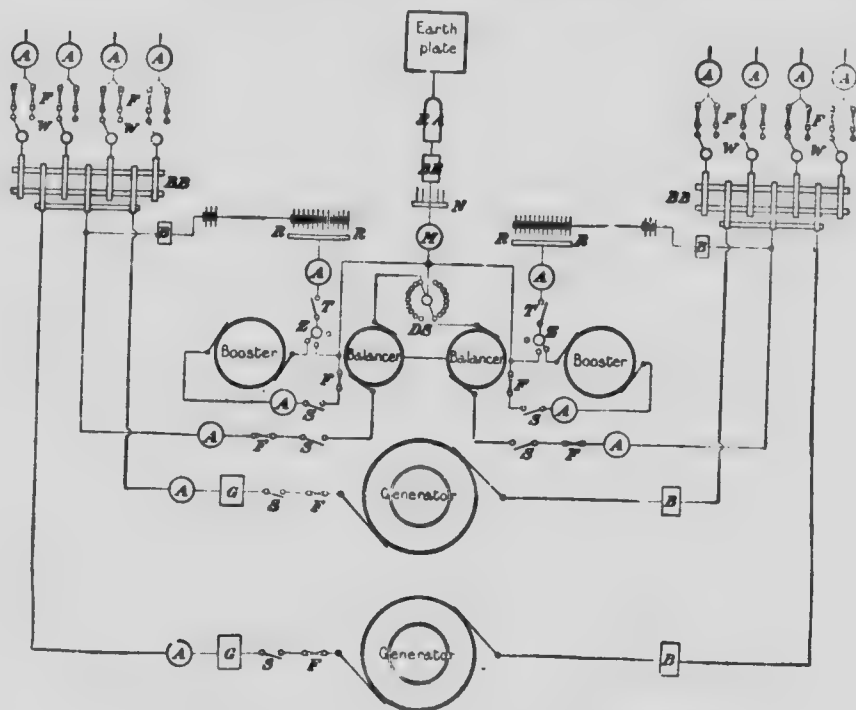


Fig. 528.—Principal Connections of the Directly Operated "Gridiron" Switchboard.

arranged as shown in Fig. 528, and by means of the screwed and coned plugs seen in Fig. 527 any vertical bar can be connected to any horizontal bar through the thickness of the board, so that any one of the feeder vertical bars can be connected either to a generator or to the battery by choosing the appropriate plug connection. This system is frequently known as the "gridiron" system, and it enables the operator to supply, if necessary, different voltages to different feeders of the system. In Fig. 527 the generators, the battery and the feeders are shown as being all in parallel on the top busbars. From the feeder vertical strips the current received in this way passes through the single-pole two-way switches w and

fuses F to the ammeter A and away, the out-of balance current returning by the middle wires to the neutral bus-bar N (Fig. 528). It will be noticed that each feeder is supplied with fuses in duplicate, so that if one fuse blows the other can be switched on quickly; this is a very convenient arrangement when the blowing of the fuse is due to its own defect and not to any fault in the system.

The two sections on either side of the central one contain the apparatus for handling the $-$ and $+$ halves of the battery, each half having its own booster as well as a cell-regulating switch R R, both at the earth end of the divided battery. The large hand wheel, marked R in Fig. 527, controls the number of cells; from this wheel the current passes through one of the ammeters A (Fig. 528) at the top of the board and then to the single-pole switch T at the bottom of the section. From this switch the current passes to a special change-over switch, marked Z in Fig. 528, whence it passes either direct to the neutral busbar N or through the booster, and then through one of the two switches S below the hand wheel, through the fuse below it, and through another of the ammeters M to the neutral busbar. The other switch, fuse, and ammeter are for connecting the busbar side of the balancer, when it is in use, to the insulated end of the battery which is connected to the busbar through a single-pole circuit breaker B.

The two smaller hand wheels above the cell-regulating hand wheel work the rheostats for the control of the shunt excitation circuits of the booster and balancer on that side of the system. Between them there is a voltmeter switch for throwing any of the different voltages on to the large station voltmeter above the corresponding end of the board. For clearness all these are omitted from the diagram.

On the central section of the board the circuit breaker B E (Fig. 528) at the bottom and the recording ammeter R A at the top are between the middle wire and the earth plate. The hand wheel in the centre is a double-starting switch D S (Fig. 528) for the two balancers, and the ammeter M measures the out-of-balance current. The action of the balancers and boosters will be explained more fully later.

The requirements for electric light and power on board ship are most conveniently met by a low-voltage continuous current system. The conditions of working are usually severe, especially with regard to the space available, and thus examples of compact switchboards occur frequently. This quality of compactness was the outstanding feature of the earlier types of directly operated non-panel boards, which therefore may be further illustrated here by an example in which the requisite compactness is secured so as to satisfy more modern conditions. Such a board, supplied by Messrs. Ferranti, Limited, for the well-known Cunard steamship *Mauretania*, is illustrated in Fig. 529, which represents one of two duplicate boards installed. The two boards are separated by a water-tight bulk-

head: that if either engine room be flooded the electrical supply can be controuled from the other.

The board consists of two generator sections, one at either end of the board,

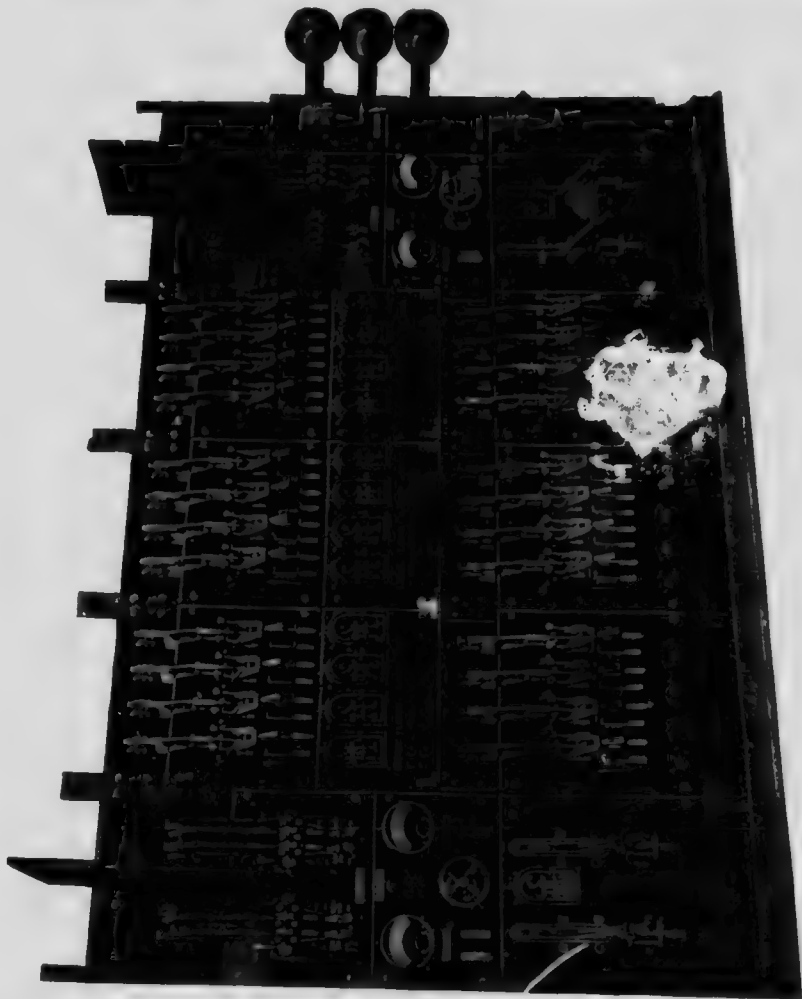


Fig. 599.—One of the Switchboards of the *Manitania*.

and a coupling section on the extreme right to couple the two boards together. In the centre are the switches, etc., for twelve feeder circuits, arranged on six sections, three positive at the top and three negative at the bottom, with ammeters on the positive side. All the switches are in the form of automatic circuit breakers. The two main switches for the generator are worked by the

handles down at the bottom of the board, which are so placed that at the moment of closing full power can be thrown on the lever, which thus closes the circuit breaker firmly. Two ammeters, and the rheostatic control, are in the centre of the generator section, and also the voltmeter plug switch. There are also voltmeter plugs for each feeder, the voltmeters being on swinging brackets at the end of the board. Notice that the two circuit breakers for each generator, one on each lead, are practically cellular, being separated by a slab of insulating material sufficiently substantial to prevent flashing over if the circuits are opened under load. The working voltage is 120 volts, and the circuit breakers can carry 4,000 amperes continuously, or 5,000 amperes for an hour. Each is fitted with a time-limit overload and reverse current relay. The feeder circuit breakers have both series and shunt tripping solenoids, the shunt coil connected across the busbars and the series coil in series with the feeder. The two coils are employed because it is undesirable that the feeder circuit breakers should be tripped and opened readily, as this would withdraw current from a large section of the ship. The sub-circuits throughout are protected by fuses, and it is better that, for an ordinary fault, the fuse should blow rather than that the main circuit-breaker should open. The shunt tripping coils are therefore worked with a time-limit relay, and if a fault occurs on an insignificant section of the system the time-limit relay gives time for the fuses to blow before the circuit breaker opens, so that the whole section of the feeder is not deprived of current unless the short circuit is a very serious one. On the other hand the series tripping coils of the circuit breakers are set to open for an overload of not less than 500 per cent. For a bad short circuit upon the feeder, the circuit breakers would therefore open straight away. The small section at the voltmeter end of the board only provides the coupling switches for coupling together the busbars of the port and starboard duplicate boards.

Panel Boards.—In the early days of the development of electric generating stations the switchboard was usually designed to satisfy the special conditions of each station, and even the apparatus and instruments used were not always specially constructed for switchboard work. Consequently, if and when required by extensions, it was frequently necessary to reconstruct the board almost *de novo*, and, moreover, when anything went wrong special work and expert knowledge had to be requisitioned. Extensions and repairs were therefore expensive matters. With the growth of the industry the desire to diminish these costs, and other reasons, rendered economical the standardisation not only of apparatus and instruments, but also of their arrangement on the board according to the particular operation which was being dealt with. This led almost inevitably to the panel system, in which the over-all function of the board is subdivided, and the apparatus for a particular machine or subsection of the work is

collected on a small sub-board or panel, the whole board being built up by assembling and mounting a sufficient number of these panels along side one another. In a generating station the panels required are usually (i.) generator panels (one for each generator), (ii.) feeder panels (one for each feeder or group of feeders), and (iii.) battery panels, with or without booster panels; exciter panels may also be necessary for A. C. work. On large boards subsidiary panels—such as a standardising panel, busbar connector, and coupling panels, synchronising panels, etc.—may also be required.



Fig. 530.—C. C. Generator Panel Board at the Northampton Polytechnic Institute.

It is obvious with such a system that when extensions are required new panels can be added to the already existing board and, in the event of a serious breakdown on the board, a damaged panel may be replaced by a standard panel of the same type, though this is seldom necessary, as the parts of the panel are often interchangeable as well as the complete panel.

Such systems are excellent for the objects named and in other ways, but they may be costly both as regards prime cost of erection, notwithstanding the standardisation, and also as regards the space occupied. The latter is perhaps the more serious consideration, since the actual cost of the switchboard is only a fraction of the cost of the whole station, and money wisely spent on the switchboard is well spent for reasons already given. The demands for additional space are, however, more serious, since if the board be unduly extended efficient working may be difficult, for different parts of the board will be distant from one another and not easily kept in view at the same time by the operator. In the most modern boards in large generating stations this difficulty is minimised by the method

of remote control rendered necessary for other reasons, and which will be referred to later.

Space will not permit the full description of even a small number of the different varieties of panel boards and of separate panels designed by numerous manufacturers. The principles underlying the design of all panels of the same type—e.g. C. C. or A. C. generator panels—are practically the same; and even

the connections do not admit of much variation except for very unusual work. It will therefore almost suffice to describe fully one set of boards of an up-to-date type, and for this purpose the writer selects a set with which he is necessarily familiar—namely, the panel boards in the generating station at the Northampton Polytechnic Institute in London, recently erected by Siemens Brothers' Dynamo Works, Limited.

A Continuous Current Generator Board.—The continuous current low-

voltage generator and battery board at the Northampton Polytechnic Institute is arranged on a gallery at the engine end of the machinery room, as seen in the background of Fig. 396. The board is shown separately in Fig. 530, and consists of seven panels—namely, two for the main generators on the engine shafts, two for the generators of the motor-generator set, seen on the left of the generators in Fig. 396, and three booster and balancer panels. On the extreme right of the board are two illuminated dial voltmeters on swinging brackets, the upper one being a machine voltmeter and the lower a busbar voltmeter. Any one of the four C. C. machines can be plugged on to the upper voltmeter by voltmeter

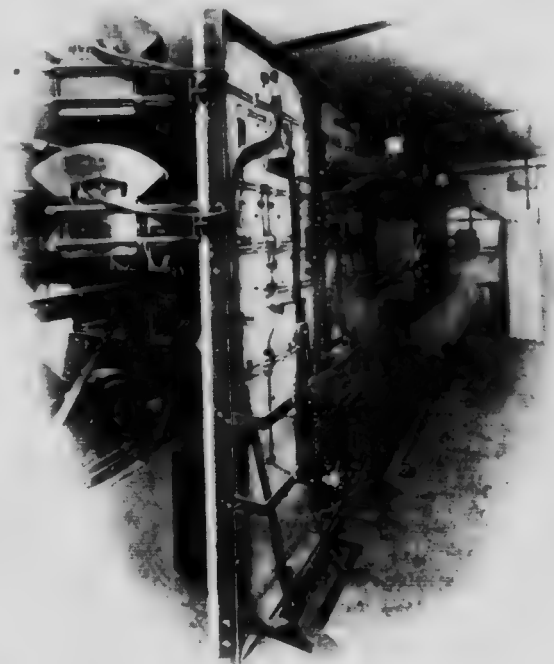


Fig. 530.—Back View of C. C. Generator Board

plugs on its own panel. A back view of this end of the board, showing some of the connections and the mounting of the busbars, is given in Fig. 531.

The four generator panels are at the right-hand end of the board, the two smaller machines being at the extreme end. The connections for the four panels are given in Fig. 532. The generators are indicated diagrammatically with their series and shunt field coils at the bottom of each panel,

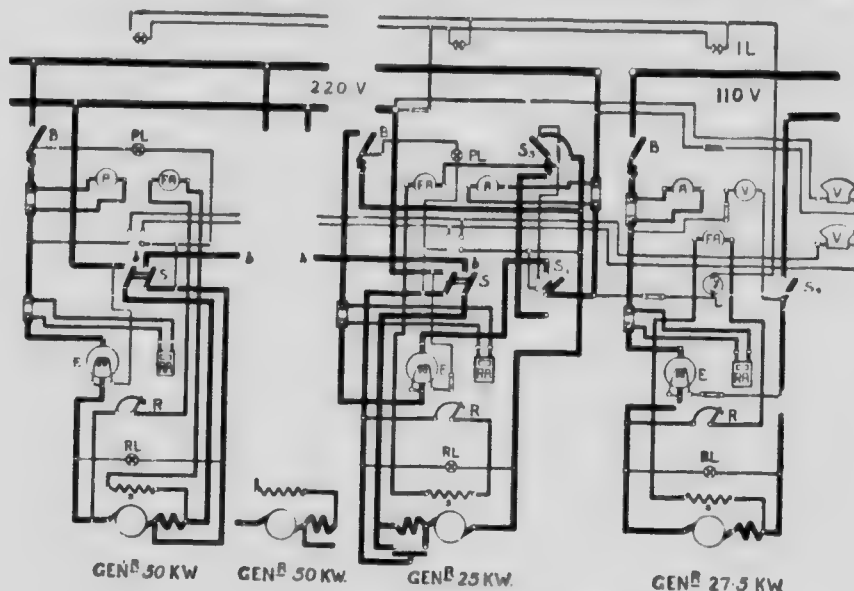


Fig. 532.—Diagram of Connections of the Generator Panels of the Board at the Northampton Polytechnic Institute

and the 220-volt busbars for the first three generators at the top. Taking first the two main (50-kilowatt) generators, it will be seen that the connections pass from the left-hand brush through the energy meter *E*, the shunts of the recording and indicating ammeters, *R A* and *A*, and a circuit breaker *B* to one of the busbars. A lead passes from the other brush through one arm of the double-pole switch to the equalising bar *b b*, which is common to the three panels. From the terminal of the machine the main lead passes direct to the busbar through the other arm of the D. P. switch. The shunt field coil is connected across the terminals of the machine through the regulating rheostat *R* and a field ammeter *F A* with no switches on circuit. Two lamps, *P L* and *R L*, are shown in the diagram. It will be found that the circuit of *P L* (the pilot lamp) is across the brushes of the machine, and obtains current from the machine direct, whether the switches *B* and *S* are closed or open. This lamp is on the panel. The

her lamp, R L, a red lamp, is mounted on the machine itself and is connected permanently across the brushes without any switch; it is placed on the machine, and both lamps come up to full brightness as the machine voltage rises.

A Continuous Current Feeder Board.—The current having been collected at the busbars of the generator board as just described, the next main operation is to distribute it to the points where electric energy is needed. This is the function of a distributing or "feeder" board. The low-voltage

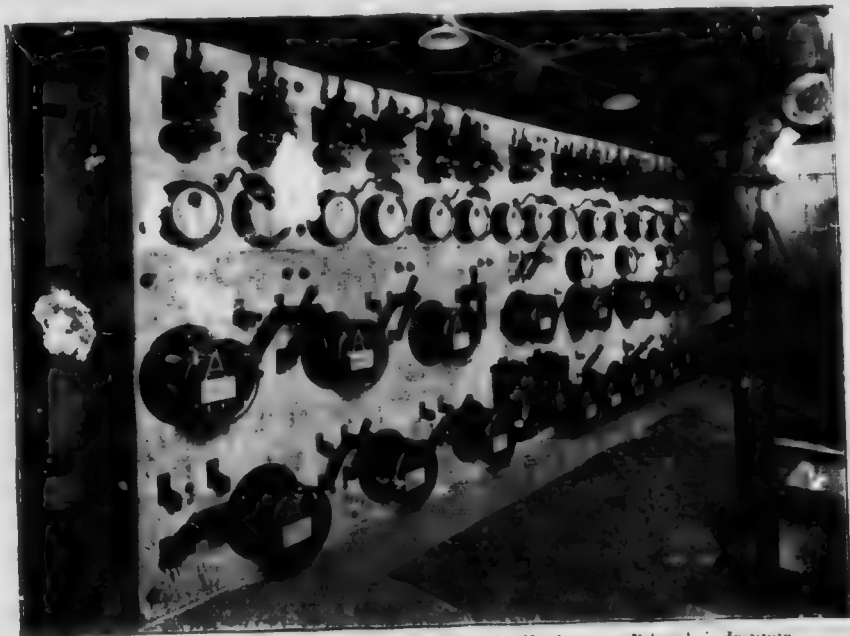


Fig. 533.—Low-Voltage C.C. Feeder Panel Board at the Northampton Polytechnic Institute.

continuous current feeder board in the generating station at the Northampton Polytechnic Institute is erected on the floor of the station underneath the gallery at the engine end of the room. It can be seen behind the engines in Fig. 306, but a better view of it is given in Fig. 533. It contains all seven panels. The first three on the left are ordinary feeder panels, feeding six circuits (two per panel) with continuous current at 200-220 volts, being the voltage across outers of the three-wire lighting system of the building. Two of these six feeders are to supply current up to 400 amperes on each feeder to the sub-station which supplies continuous currents for lighting and power purposes to the whole building. The remaining four feeders have each a maximum carrying capacity of 150 amperes, and convey current to various laboratories for experimental

purposes. The connections for one of the panels are given at w, Fig. 534. Each feeder is closed by a double-pole switch s, and in addition there is a circuit-breaker B on the $-^w$ side, set to open when the current rises above a certain value. There is also an ammeter A of the shunt type and an energy meter E in each feeder. The position of each piece of apparatus can be easily identified in Fig. 533. The equipment is simple, and all that is necessary. The busbars shown at the top of the diagram are directly connected to the busbars of the c. c. generator board in the gallery above (Fig. 532).

The sixth and seventh panels z on the extreme right are for the purpose of supplying continuous currents at 100–110 volts independently of the general three-wire system. They receive energy from the 110 volt 27.5 kilowatt

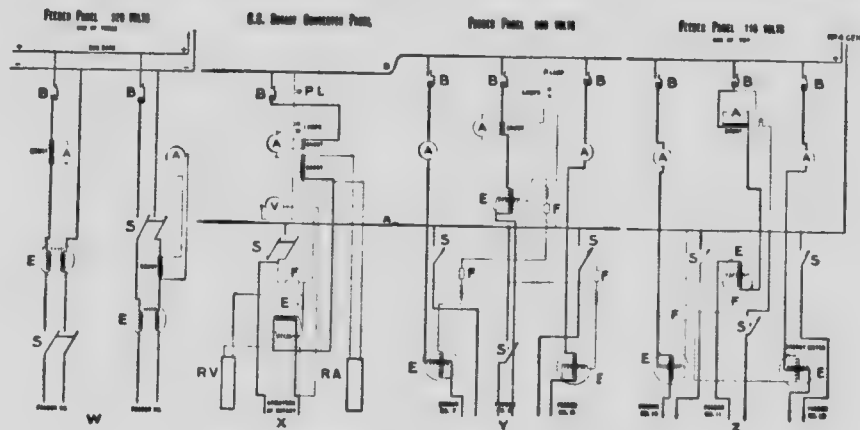
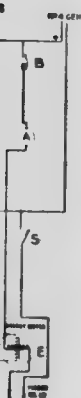


Fig. 534.—Connections of Low Voltage c. c. Feeder Board.

dynamo of the coupled plant driven by the synchronous motor. There are (see z, Fig. 534) six feeders on these panels with connections similar to those on the 220-volt panels, except that on the $-^w$ side the only switch installed is the circuit breaker and that the current coils of the energy meters are on the $+^w$ lead only. One of these feeders has a maximum capacity of 200 amperes, whilst the other five are 50-ampere feeders. The excitation current c c (Fig. 540) for the synchronous motor is taken from this panel, which also supplies current for various experimental circuits in the different engineering laboratories of the Polytechnic. There are ammeters and energy meters for each feeder, as in the preceding cases, and the pressure circuits of the energy meters are protected by fuses.

The fourth panel x receives continuous current at 500 volts from the commutator of the rotary converter. At the bottom of the panel, the connections of which are also given in Fig. 534, there are (see Fig. 533) a recording ammeter RA and a recording voltmeter RV, and immediately

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above these an energy meter *E*. Above the meter is a double-pole switch *S*, one electrode of which is on the $-$ lead and the other is for a third lead on the series coil of the rotary (see page 547). The $+$ lead is taken through the energy meter *E*, the shunts of the recording ammeter *RA* and the ammeter *A*, and a circuit breaker *B* to the $+$ busbars. The $-$ lead, after passing through its switch, goes to the $-$ busbar, and the two busbars then pass behind the adjoining 500-volt feeder panel *y*. This panel supplies current at 500 volts to three feeders, two of which carry 50 amperes each and one 100 amperes, all for experimental work. The connections and instruments for these feeders are similar to those on the other feeder panels described above.

On all the panels there are pilot lamps, marked *P.L.*, which are coloured red, and whose function is to show when the panel is alive. The reader will be able to make out easily their connections in the different cases. On the 500-volt panels the pilot lamp has two resistance lamps in series with it to reduce the voltage across its terminals. There are also illuminating lamps placed across the 220-volt busbars, but not shown on the diagram.

An Alternate Current Feeder Board.—A feeder board for low-voltage polyphase alternate currents (A. C.) is very similar to a feeder board for continuous currents (C. C.), and it will be convenient to describe one here, although we have not yet described an A. C. generator board. The chief differences between the two boards are that the double-pole switches

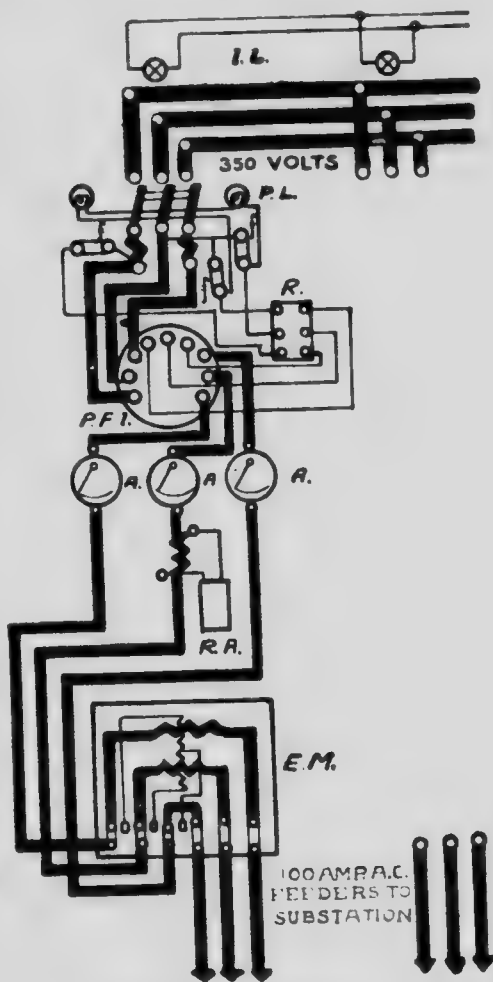


Fig. 535.—Connections of Low-Voltage A. C. Feeder Board.

of the c. c. feeder board have to be replaced on the A. c. by multiple switches appropriate to the number of phases, and that the instruments mounted on the board differ in type and number. Fig. 535 gives the connections for one panel of the low-voltage A. c. feeder board at the Northampton Polytechnic Institute; the actual board will be described later (see Figs. 542 and 543). Three-phase currents of the proper voltage, about 350 volts in this case, are supplied to the busbars from the transformer panel of the remote-control board (see page 549) either directly or through the A. c. regulating panels described on page 545. From the busbars currents are taken to the feeder through a triple-pole switch after which they pass through (i.) the current coils of the power factor indicator PFI, (ii.) the three ammeters A, one in each phase, and (iii.) the current coils of the energy meter E M. The pressure circuits for PFI are taken off the phases through fuses *f* and resistances R, but the pressure circuits for E M are obtained by connections within the instrument, this being rendered possible by the fact that all three current phases pass through it. In addition a recording ammeter RA is placed through a current transformer on one of the mains, and a pilot lamp PL, with a lamp resistance in series with it to reduce the voltage, is placed across one of the phases. The reader should compare this equipment with the corresponding equipment on a continuous current feeder panel, as shown in Fig. 532.

Regulating and Battery Switchboards.—One of the functions of a switchboard to which reference has already been made is to regulate the distribution of the current collected on the busbars to the various feeding circuits along which the current is to be transmitted to the places where it is to be utilised. In a large station, especially if heavy currents are being handled, the successful operation of this function requires the solution of some interesting problems. As an instance, take a continuous current station which is supplying a heavy tramway and lighting load spread over a considerable area. There are bound to be going out from the station feeders to various points, some of which are close to the station and some at a distance. On light loads the fall or drop of the voltage along a feeder is a comparatively unimportant matter, but when the load becomes heavy with reference to the capacity of the feeder, then the drop becomes an important quantity, unless there has been extravagance in laying down the feeder in respect of the amount of copper used. In times of heavy and possibly unequally distributed loads, it is necessary to raise the voltage at the station end of certain feeders above the normal, so that at the far end the voltage may not be lower than the normal. In some cases this is accomplished by having multiple busbars, that is, two or more sets of busbars kept separate, when necessary, from one another, which means practically keeping up the voltage of certain feeders by putting particular machines on to them, and raising the voltage of these machines by over-compounding or otherwise. This, however, is

breaking down the busbar principle, which is that all the generators are upon common busbars from which all the feeders are supplied.

Now, it is obvious that there is another way of satisfying the conditions, and that is to interpose between the busbars and the long-distance feeders at the proper time some volt-raising device which will raise the voltage at the station end of these feeders. This system is known as "boosting," which must not be confused with the use of a secondary battery to carry over periods of heavy load. That, of course, is another very important part of central-station practice, and may be conveniently and briefly referred to here. Figs. 536 and 537 show winter load curves of the Dickinson Street Station of the Manchester Corporation. The curve in Fig. 536, including the peak at 5.0 p.m., is the load curve on the station on a winter

day. Without a battery, the power required would have to be supplied by the generating plant running throughout the twenty-four hours. The load factor of this curve is 32 per cent., and is a good load factor, because of the heavy day load,

due chiefly to the tramway demand, for this is both a tramway and a lighting station. The diagram shows that between 4 o'clock and 7 o'clock in the evening, there is a heavy peak due, without doubt, to the superposition of a lighting load upon the power load, which at this time is augmented by the load of the rush hours.

It will be noticed that the top of the peak is at 11,000 kilowatts, whereas the day load is about 4,800 kilowatts. This excessive load, which only lasts for about three hours, more than doubles, when at its highest point, the demand made on the station. It is the chief function of a battery to tide over the peak as well as to allow the machinery to be stopped during the night, when the load is very light. The shaded portions of the diagram show the amount of energy which may be taken out of a battery whilst fulfilling these two objects, the maximum demand on the generators falling from 11,000 to 8,600 kilowatts during the peak interval, and the generators being altogether shut down from a little after 11.0 p.m. until 6.30 a.m.

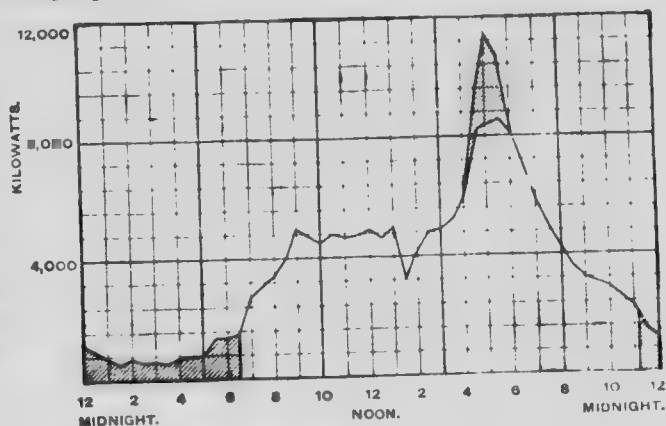


Fig. 536.—Station Load Curve without Battery.

The energy thus given out by the battery has, of course, to be put into it whilst the machinery is running, and in Fig. 537 is shown the load curve on the generators whilst running from 6.30 a.m. to 11.20 p.m. The station load curve for the same period has been re-plotted below the other curve, and the shaded space between the two curves shows the energy put into the battery during working hours. The general result is that the generators run not only for a shorter period, but also with a higher load factor, for the load factor for the upper curve on Fig. 537 works out at 43.5 per cent., as against the 32 per cent. of Fig. 536. The load factor is thus increased by more than one-third. The battery cannot do this, however, without some kind of regulation. In some cases regulation is effected by altering the

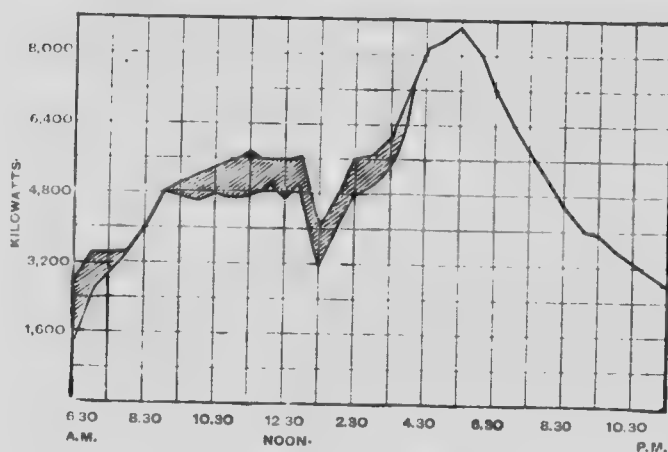


Fig. 537.—Plant Load Curve with Battery.

number of cells in the battery, an instance of which has already been given at page 522. The difficulty is that for a fixed number of cells a battery has what is practically a voltage which varies within certain fairly wide percentage limits. When the battery is discharging, its P. D. is below its E. M. F., and when it is being charged, the P. D. has to be above the E. M. F. of the battery. Moreover, the E. M. F. itself rises during charge and falls during discharge. Therefore, some regulation is absolutely necessary. It is here that "boosting" again may be employed, the boosters making it possible to work with a battery having a fixed number of cells, and to get rid, not only of the difficulty and complications of changing the number of cells in the battery, but also of the effect of these changes upon the cells themselves. When regulating by changing the number of cells, the regulating cells are not treated with the same amounts of charge and discharge as the other cells of the battery. Thus, regulating cells, when used, are a source of weakness in the battery, and one of the advantages of using boosters is that they get over the difficulties involved in using such regulating cells.

It should be explained here, that the most common form of booster

consists of a motor, a generator and an exciter, usually mounted on the same shaft. The motor is designed to run off the busbars, and is usually hunt wound, with or without some speed-regulating device. It drives the generator, which is either wholly or partially excited by the current from the exciter, and is designed to carry a very heavy current, namely, the full-load current of the feeder, or other device, on which the voltage has to be raised. The exciter is designed to supply either a positive or negative current to the generator, and when the set works automatically its current, both in direction and quantity, is made to depend upon the amount of "boost" actually required.

A Battery Booster Regulating Board.—The regulation required on a constant-voltage system when a secondary battery is employed as an auxiliary has already been briefly referred to on page 523, when regulating cells and boosters were both employed. As just explained, with a well-designed booster, the regulating cells may be dispensed with. The several types of boosters will be fully dealt with later.

A diagram of the connections of the booster panels at the Northampton Polytechnic Institute, is shown in Fig. 538. These panels are placed at the left-hand end of the generator-board already illustrated in Fig. 530. There are two panels, and in the figure the battery BB is represented diagrammatically between them. The main M_1 from the $+$ busbar passes through three shunts direct to the single-pole circuit breaker C . The first shunt terminals supply current to the ammeter A on the adjoining panel. This is a polarised ammeter, showing by the direction of the deflection whether the current in M_1 is a charging or a discharging current. The second and

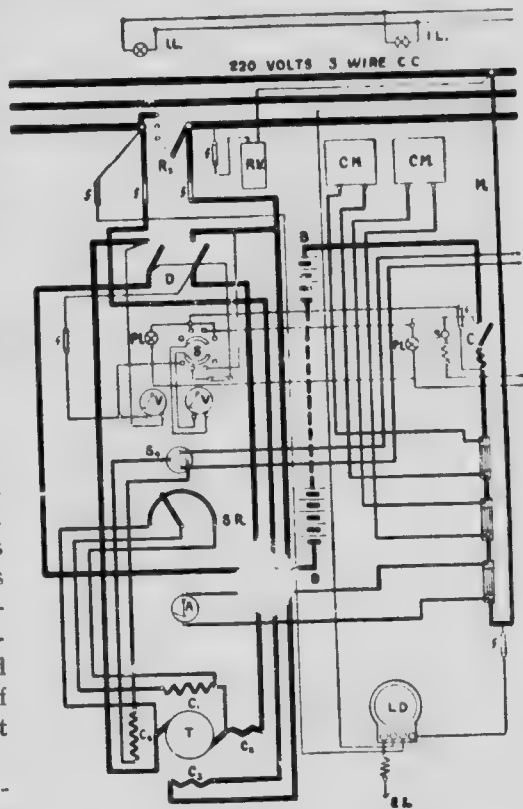


Fig. 538.—Connections of a Battery Booster Regulating Board.

third shunt terminals supply current respectively to the discharging and charging coulomb meters $C M$ at the bottom of the panel. One of these meters integrates the total charge, and the other the total discharge, the readings being in ampere-hours. From the circuit-breaker C the current passes direct to the $+$ pole of the battery from the $-$ pole of which a connection is made to the left-hand arm of the double-pole switch D . When this switch is closed, the connection is continued to the left-hand brush of the booster T , whose right-hand brush is connected, through its series field coil c_s , to the right-hand arm of the switch D . When this arm is closed the connection is continued to the $-$ busbar, and the circuit is complete. The electrical effect is that the battery and the booster are placed in series with one another across the outer busbars of the three-wire system.

In addition to the main circuit, there are several subsidiary ones. The shunt excitation coil c_1 of the booster is taken directly off its brushes, through the hand-regulated rheostat $s R$, part of which also acts as a discharge resistance for the shunt field. There are two voltmeters V on the panel. The left-hand one shows the voltage across the brushes of the booster. The right-hand voltmeter is connected to a multi-contact voltmeter switch s , by turning which different important voltages can be ascertained; the reader should trace out these connections for himself. There are also two auxiliary excitation coils, c_3 and c_4 , on the booster; c_3 is interposed between the generator $-$ busbar, and the lighting $-$ busbar in parallel with the resistance of the adjustable rheostat R_3 , whilst c_4 , which is shunt wound, receives current from the two sides of the balancer (see Fig. 539), through the reversing switch s_4 . The connections of the pilot lamps $P L$ can be readily made out, and are interesting.

A Continuous Current Balancer Regulating Board.—The object of the continuous current balancers, already briefly referred to on page 523, is to act as regulators on a three-wire distributing system. On such a system the load should theoretically be always the same on the two sides, in other words, the loads on the two sides should balance. In practice this ideal state of things cannot be attained, for, as a rule, the two loads are unequal, sometimes in one direction, sometimes in the other. When this occurs the supply voltage across the outers will not be equally divided between the two sides, unless some regulating device is employed. It is the function of the balancers to supply this regulation automatically, or, to put it colloquially, to take charge of the out-of-balance current. The machines used may be regarded as motor-generators, and their application for this purpose has been described at page 635 of Volume I.

The connections of the balancer panel at the Northampton Polytechnic Institute are shown in Fig. 539, the actual panel being mounted on the generator board (see Fig. 530) between the booster panels just described

and the generator panels. The projecting connections on the left-hand side of Fig. 539 are continuous with the corresponding projections on the right-hand side of Fig. 538. The two balancer armatures x x have their extreme brushes right and left directly connected to the outers of the three-wire system through the single-pole circuit breakers CB , the incoming leads carrying shunts whose terminals supply current to the two ammeters AA , which respectively show the currents on the two sides. The inner brushes of the armatures x x are connected respectively to the two sides of the hand-rheostat H_0 , the middle of whose arm is connected to the middle or neutral wire of the three wire-system, through (i.) the two series excitation coils k of the balancers, (ii.) the ammeter shunt s , whose terminals supply current to the third ammeter A_3 , and (iii.) the single-pole switch s at the bottom of the panel. The ammeter A_3 , therefore, measures the out-of-balance current coming from the neutral wire, and it is a polarised instrument, so that the direction of this current can be observed. The voltmeters v , which are at the top of the panel, and the recording voltmeters RV at the bottom will be found to be connected so as to show and record respectively the voltages on the two sides. The shunt excitation of the two balancers is interesting. On examining the connections of the two coils h_1 h_2 it will be found that h_1 , the coil of the left-hand machine, is connected between the outer brush of the right-hand machine and the left-hand end of the hand-rheostat H_1 , and that the coil h_2 of the other machine has the corresponding connections on the other side. The movable switch arm of H_1 is connected to the incoming lead from the neutral wire. It will be useful for the student to work out how it is that the conditions of regulation make it desirable to cross over the excitation circuits in this way, it being remembered that the shunt excitation is the principal excitation of each machine, and that the object of the armatures is to raise the voltage where it is too low and depress it where it is too high. It should also be borne in mind that both armatures are on the same shaft and run at the same speed.

A Combined Battery and Booster Regulating Board.—As an example,

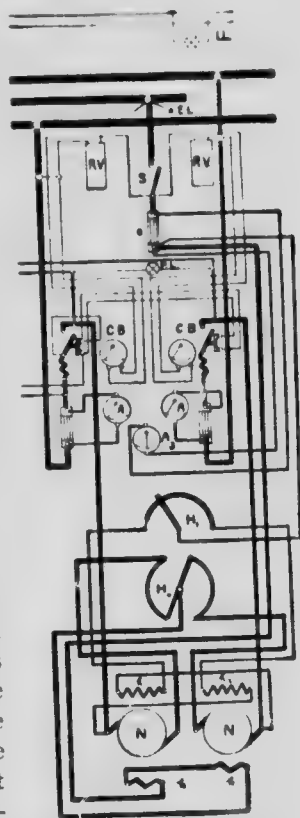


Fig. 539.—Connections of a c.c. Balancer Regulating Board.

taken from a large public supply station, of a separate regulating board in a case where both an auxiliary battery and boosters are used, Fig. 540 shows a regulating board used in the Dickinson Street Station, from which the curves in Figs. 536 and 537 were taken. This board has to handle 15,000 amperes at 600 volts, it therefore takes charge of 9,000 kilowatts; there are no regulating cells on the battery. The board, designed and built by Messrs. Ferranti, Limited, is divided up into ten panels. The battery is on the first panel on the left-hand side, then there comes a diverter panel, and next to that is what is known as a booster short-circuiting panel. Farther along, there are three pairs of panels, which are the booster motor and generating plants for three sets of boosters; and then, finally, at the far end, are the exciter panels, the exciters in this case being separately driven.

There are two ways in which a booster may be worked, automatically and non-automatically, and one advantage of taking this particular example is that both systems are in use. A diagram of the connections is given in Fig. 541. The station being for traction and lighting purposes, there are two sets of busbars—one $T_1 T_2$ for traction and the other $L_1 L_2$ for lighting. There are also three other busbars, two booster bars B_1 and B_2 in connection with the traction section of the board, and one booster bar B_3 in connection with the lighting section. With this board, connections can be made, so that the battery can float, as it is technically called, on either the lighting or the traction bars (i.) with any one of the three boosters in series with the battery, or (ii.) with two boosters coupled in parallel and put in series with the battery. In addition (iii.), on the traction bars, two boosters can be put in series with one another and in series with the battery, and (iv.) on the lighting side three boosters can be put in parallel amongst themselves and in series with the battery, but as there is only one extra booster bar, two boosters cannot be put in series with one another on this side.

The boosters themselves can take currents of 3,800 amperes and change the voltage by a maximum of 120 volts, the working voltage being 600 volts. Each booster set consists of a motor and a generator on separate panels, and there are two exciter sets on the end panel of the board, each with its motor and its generator. The generators of the booster sets are none of them self-exciting; the excitation is supplied from the exciters through the exciter busbars $e_1 e_2$, or they may be supplied from the excitation circuit of the motor, and in that way they may be indirectly self-exciting.

Taking the battery panel first from the $+$ end, the current goes through a circuit breaker (b , Fig. 541) through a recording ammeter $R A$ and an indicating ammeter A to one of the heavier throw-over switches S_1 , which are so prominent in Fig. 540. The other end goes straight to the

other throw-over switch s_1 . The positive lead continues through charge and discharge meters to the positive busbar of either the traction or the lighting bars according to the position of the switches s_1 ; the negative lead goes to B_2 or B_3 , and can be connected by links on to either the traction or the lighting set and negative busbar T_2 or L_2 . These links or connector switches can short circuit the booster bars on to the negative bars on either side. There are voltmeters on both sides of the links, measuring the P. D.'s between the boosters and the negative busbars when

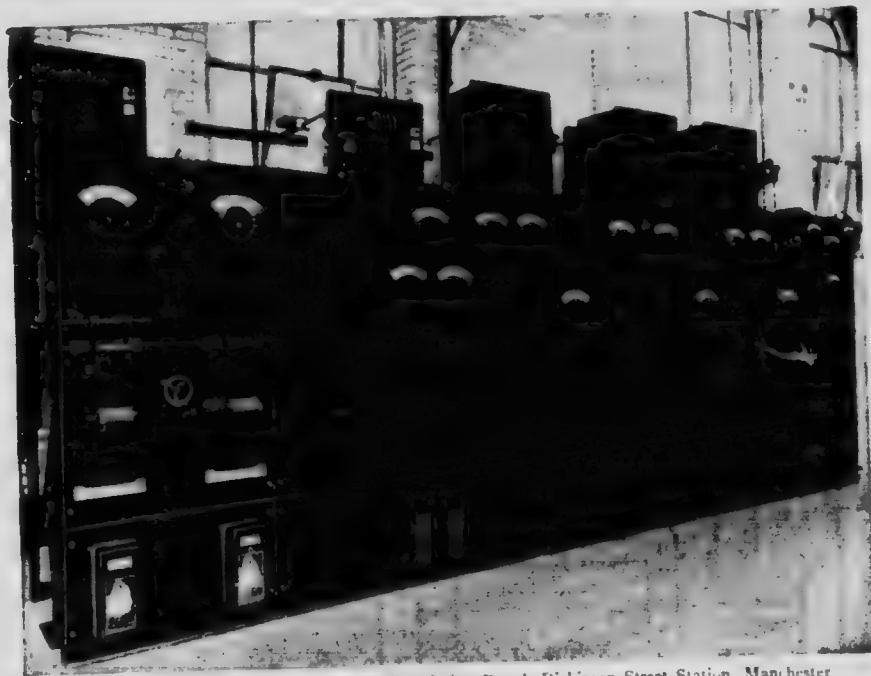


Fig. 540.—Ferranti Battery and Booster Regulating Board, Dickinson Street Station, Manchester

the links are open. There is a voltmeter on the battery panel with a multiple voltmeter switch, by which it can be put on either (i.) the traction busbars, or (ii.) the lighting busbars, or (iii.) the battery. These switches and instruments should be identified on both the diagram of Fig. 541 and the board itself in Fig. 540. The only switch which cannot be seen in Fig. 540 is the circuit breaker, which is a remote control one, having to handle, if necessary, 15,000 amperes at 600 volts. Mr. Ferranti considers that such a circuit breaker should be as carefully protected as a high-voltage circuit breaker, and he therefore puts it in a concrete cubicle by itself. All the heavy circuit breakers on this board are in separate cubicles.

Coming now to the next panel, which is the so-called diverter panel, the negative current from the traction generators, or from the battery in

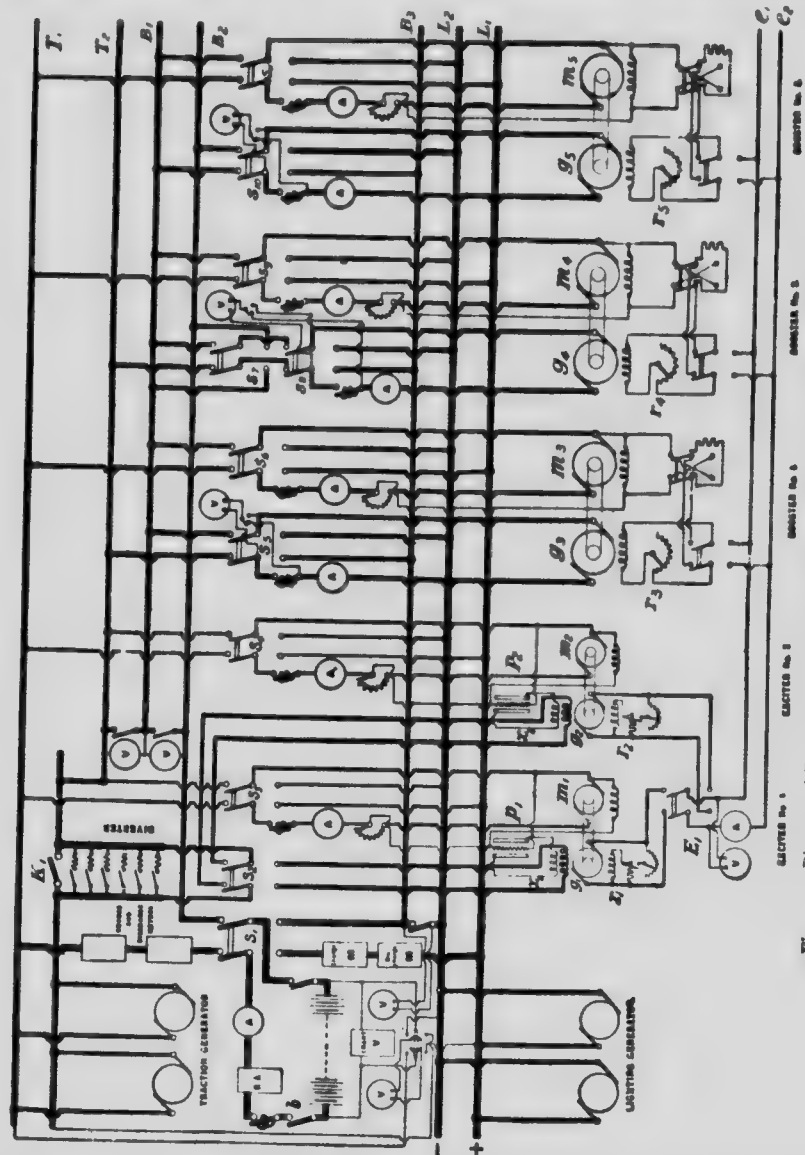


Fig. 541.—Diagram of Ferranti Regulating Switchboard, Dickinson Street Station, Manchester.

parallel with them, passes direct to the busbar if the link K_1 , Fig. 541, be closed, but by opening that link the current is passed through one or

more of the resistances, which are known as diverter resistances. The object of these resistances is to be put in parallel through the throw-over switch s_2 with the series excitation coil of the generator of either of the exciter sets. Only one exciter set is wanted at one time, and by throwing over s_2 the series or compounding coil, which is the controlling coil of the set in use, can be put in parallel with those resistances, and, therefore, the current through that coil will be proportional to the load current passing to the traction busbars, which will thus control the exciter current of the boosters.

The exciters g_1, g_2 (Fig. 541), are driven by motors m_1, m_2 , which, by throwing over the switch s_3 or s_4 , can be put either on to the traction busbars T_1, T_2 or on to the lighting busbars L_1, L_2 . The motors have circuit breakers on the "+" lead and ordinary shunt excitation, but with a controlling resistance in the armature circuit, by which the speed and powers of the motors can be altered. The adjustment is by hand-controlled switches, and is not automatic. The fields of the exciter generators are more complicated. There are two shunt-exciting coils, and one series. The series coil has already been referred to as being in parallel with the diverter resistances, and carrying a current which fluctuates with the load, but not taking the whole load current, thus avoiding the disadvantages of carrying a 15,000 ampere current through a field-magnet coil. The shunt excitation, r_1 or r_2 , is the ordinary excitation with a discharging coil, controlled by a rheostat in series; the other excitation, x_1 or x_2 , is also a shunt or small current excitation-shunt relay, which is supplied with current from a potentiometer resistance p , by which the voltage on the coil can be altered and set to any value desired by contacts on the resistance, and thus this auxiliary shunt excitation can be set to a definite value. Either of the two generators through the change-over switch E_1 can be put on to the exciter busbars e_1, e_2 , but it is impossible to put the two machines on to the busbars simultaneously. On the busbar side of the switch there is an ammeter A and a voltmeter V .

The three booster sets are each driven by a motor, m_3, m_4 or m_5 , which can, by the D. P. throw-over switches, s_6, s_9 or s_{11} , be put directly on to the busbars T_1 and B_1 on the traction side, or on to the busbars L_1 and L_2 on the lighting side, but not on to the two sides at once. The excitation is simple shunt excitation across the busbars used with rheostatic control in the armature circuit, and circuit breakers in the positive leads in each case. In the generator circuits of boosters Nos. 1 and 3, which are similarly connected up, except as regards the busbars used, there is also a throw-over switch, s_7 or s_{10} , with an ammeter and a circuit breaker on the "+" lead. There is also a voltmeter, which by an appropriate switch can be interposed between one side of the main throw-over switch and either generator lead. Generator g_3 can

be put on bars $T_2 B_1$ or $L_2 B_3$, and generator g_3 on bars B_1, B_2 or on $L_2 B_3$.

The excitation of the generators g_3 and g_4 can be taken directly off the exciter bars $e_1 e_2$, and is then automatically controlled by the load on the traction side. The shunt rheostat, r_3 or r_4 , is set in a certain position, and then the exciters are to give the necessary excitation for any voltage between the brushes from 0 up to 120 volts. The armature has, of course, to carry its share of the heavy current load. The excitation circuits of any one or more of the generators g_3, g_4 and g_5 may, however, be taken off the exciter busbars, and may be put in parallel through a rheostat with the shunt circuit of the corresponding motor. Moreover, in these connections there are reversing switches. In this case, the control is non-automatic. All these switches and instruments should again be identified on the actual board, as depicted in Fig. 540.

The connections of "Booster No. 2" are more complicated. This generator can be put on the traction side on to the busbars T_2 and B_1 , or on to the busbars T_1 and B_2 , and thus take its place in the combinations referred to on page 538. This is accomplished by having two throw-over switches in its armature circuit, as shown at s_7 and s_8 . The switch s_8 can also throw g_4 over from the traction to the lighting sides or *vice versa*. The combinations can be readily made out by examining the diagram. These combinations have all been thought out for the particular requirements of a particular station; what should be noticed is the way in which this flexibility of working can be obtained. There are several interesting points in connection with the construction of the switches and circuit breakers used on this board, to which reference will be made later if space permits. It may, however, be mentioned here that the heavy change-over switches on the first panel (Fig. 540) of the board were very carefully designed so that the current should have as little resistance as possible to flow through in passing through the switch. The test shows that when the switch is carrying 10,000 amperes the drop of pressure over the switch is 5.5 millivolts, or 0.0055 volt only; this gives a resistance of 0.55 microhm only.

Mention has been made of the circuit breakers being enclosed in concrete cubicles. It may be added that each of the busbars, which are throughout made of aluminium, is enclosed in a concrete trough, thus carrying out the Ferranti principle of isolating the important parts, even on a low-pressure board.

An Alternate Current Regulating Board.—As a good illustration of the difference between a regulating board for alternate currents and the boards already described for similar purposes for continuous currents, Fig. 542 shows the connections of the regulating panels of the low-voltage alternate current switchboard at the Northampton Polytechnic

Institute. The feeder panels which are erected alongside the regulating panels and take current from the busbars, which are energised through the regulating panels, have already been described at page 535 (Fig. 535).

Two views of this board are given in Figs. 542 and 543, and a view of the connections in Fig. 545. The board is erected on the same principle as the desk control board (Fig. 546), and the lower part of it can be just seen to the left of the clock in the view of the station given in Fig. 395, page 379. In Fig. 542, which shows the front of the board, the two nearest panels are the regulating panels and the two farthest the feeder panels of Fig. 532. A back view of the board from the same end is shown in Fig. 543, in which the busbars, supported on porcelain insulators, and other details can be readily made out.

It is noted elsewhere (page 551) that the low-voltage secondaries of the large transformers supply two sets of three-phase leads. Of these

the chief are the main leads *M* bringing in the full pressure, about 250 volts, of the transformer secondaries and the others *T* are the tapping points from close to the neutral point of the *Y*-connected secondaries, and supplying current at about 60 volts for starting the rotary converter.

The main leads *M* pass first a three-phase controlling switch *B*, whose function is to raise or lower the voltage coming from the main transformers before the currents pass to the busbars shown at the top of the diagram. This function is accomplished by means of additional small transformers, whose circuits are shown in the diagram, the whole arrangement acting

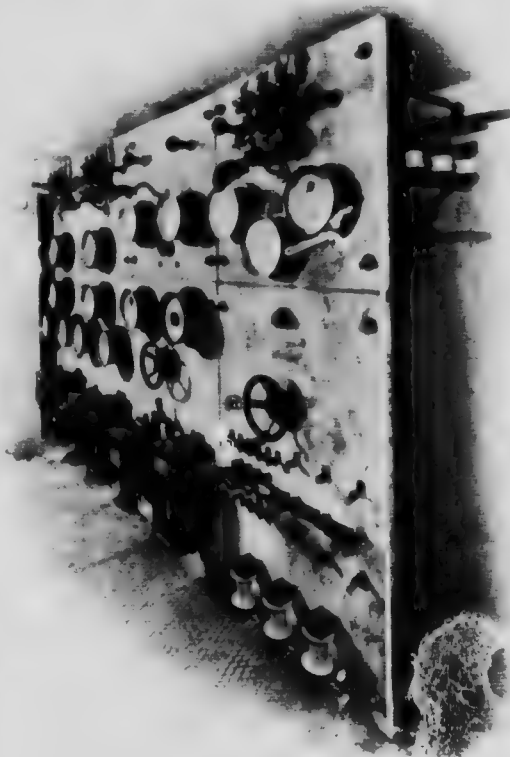


Fig. 542.—Low-Voltage Regulating and Feeder Switchboard.

as a booster either positive or negative. The connections which are referred to more fully below are somewhat complicated, although the principle used is easily followed. The actual switch is not on the board, but is mounted on the gallery below the board, from which it is operated by a chain and

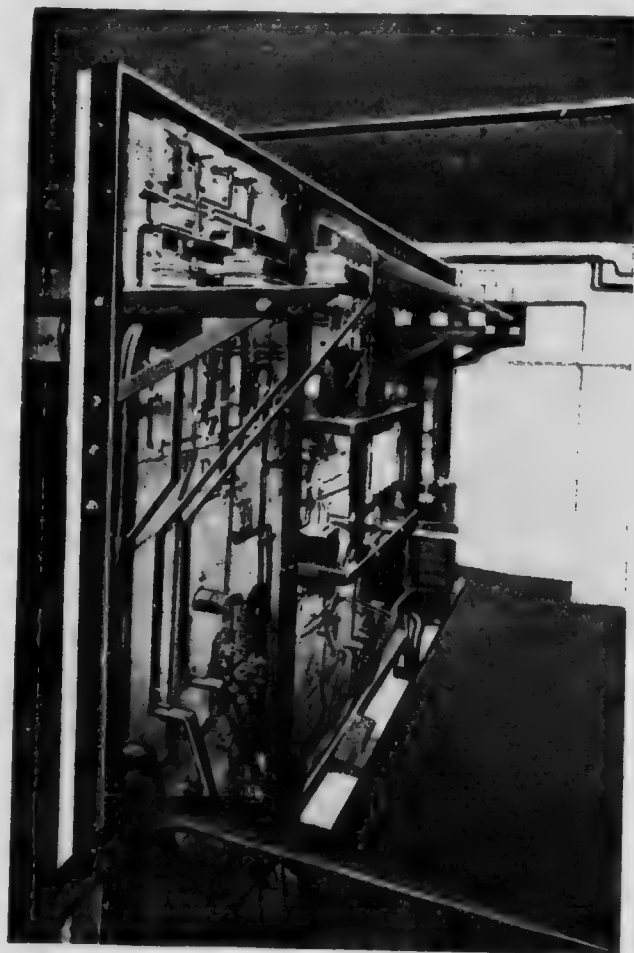


Fig. 543 —Back View of Low-Voltage A. C. Switchboard

sprocket wheel worked by the hand wheel shown on the front of the board in Fig. 542. The chain can also be seen in Fig. 543, the back view of the board. The actual switch with some of its connections is shown in Fig. 544, from which it will be seen that the contact arms are worked through gearing from the sprocket wheel driven by the chain, and that there is a crank handle by which the switch can be operated from the floor of the engine room as well as from the gallery. The boosting transformers are placed on the right-hand lower wall behind, and close to, the switch.

The voltages of the three phases are raised or depressed simultaneously by the three arms of the switch, and it will therefore suffice to follow one set of connections through. Examine the right-hand lower section of the diagram of the switch in Fig. 545. It will be noticed that there are four concentric sets of contacts: (i.) an outer set consisting of nine studs joined together

n pairs with the central one single, (ii.) and (iii.) two intermediate sets each of three extended circular segments, and (iv.) a single inner segment. The transformer is shown diagrammatically at the side by a long primary coil and a secondary coil divided into four sections by five tappings, which are connected to the five pairs of the outer ring of studs. The incoming main M_1 , is connected directly to the lower outside tap, and the outgoing main M_2 , on its way to the busbars is connected directly to the inner segment (iv.). The rotating arm connects the outer stud, upon which its finger (Fig. 544) rests, directly to this inner segment, and this outer

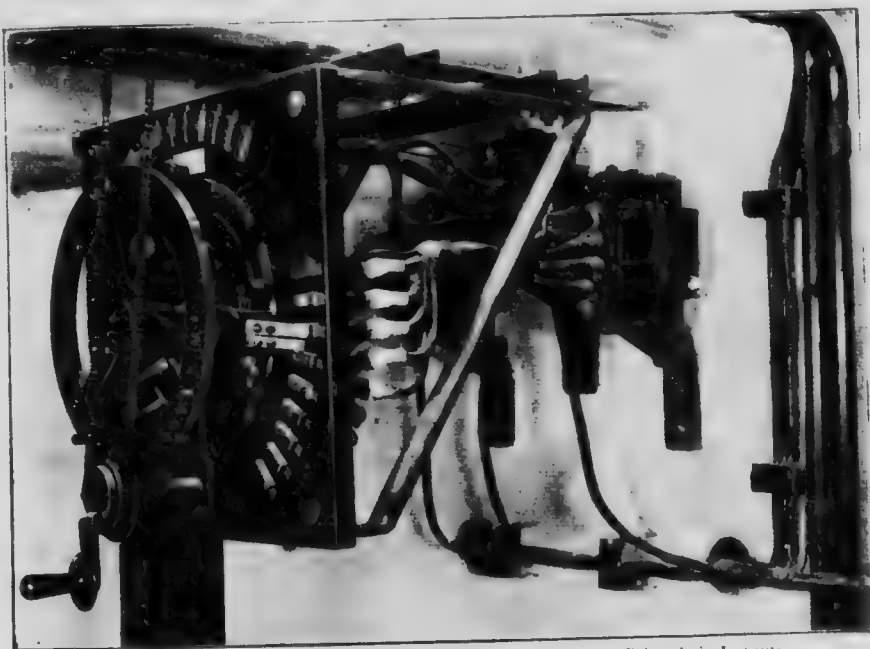


Fig. 544.--A. C. Booster Transformer Switch at the Northampton Polytechnic Institute.

ring of studs marks the limit of its rotation. On the two intermediate circles No. 1 of the outer is connected always to No. 3 of the inner, and No. 1 of the inner to No. 3 of the outer, and the two ends of the primary coil are connected to segments Nos. 1 and 3 of the outer ring. The central inner segments of all three phases are connected together, forming a neutral point for a "star" connection of the primaries, and the central outer segments are joined to the incoming main M_1 by being connected to the central stud of the outer ring of nine studs. The primaries are therefore thrown across the incoming mains as a "star"-connected system, and take the full voltage of these mains, as shown more simply in the small diagram (Fig. 546) at the side, where the currents through the switch

are set out without the complication of the reversing switch. As regards the two intermediate rings the rotating arm either links Nos. 1 and 2 or Nos. 2 and 3, and thus the six segments act as the six contacts of an ordinary reversing switch, reversing at pleasure the direction of the currents in the primaries of the transformer. This in effect reverses the end connection of the coils ϕ_1 , ϕ_2 and ϕ_3 , in Fig. 54b, and thus the main M_1 , M_2 in running

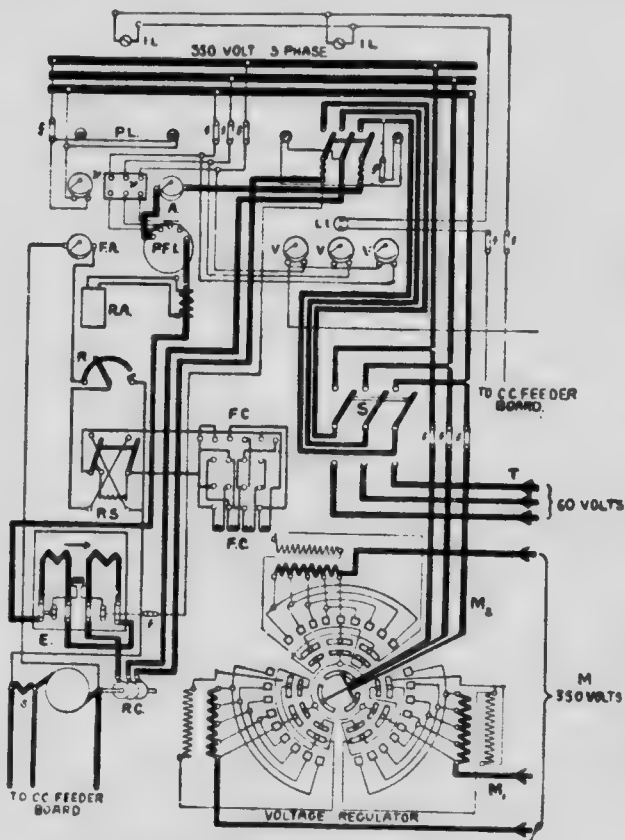


Fig. 545.—Diagram of the Connections of the A. c. Regulating Board, Northampton Polytechnic Institute.

switch S in Fig. 545 is the first step in the series of connections for starting and controlling a rotary converter (see page 635, Vol. I.). On the lower contacts it receives for starting purposes current from the 60-volt tappings T of the large transformers, whilst on the upper contacts it receives currents at the full pressure as adjusted by the booster arrangement just described. In either case the current through this switch next passes to the triple-pole circuit breakers at the top of the board.

through may find in the coils of S either an assisting or an opposing E. M. F. With each reversal of connections the voltages of all the secondaries will be reversed, and as the section of these in circuit at the moment is in series with the mains, their voltages will increase or diminish the voltages of these mains.

The general effect is that the 350 volts on the incoming mains M can be raised to 390 volts in four steps of ten volts each, or depressed to 310 volts in four similar steps.

The double throw triple-pole

From these circuit breakers two of the phases pass direct to the slip rings of the rotary converter R C, whilst the third phase on the way to its slip ring has to pass through the ammeter A, the power-factor indicator P. F. I., and the energy meter E; *en route* a current transformer gives off current to the recording ammeter R A. The instruments E and R A are at the bottom of the further panel in Fig. 542. For voltmeter purposes currents are taken direct from the main busbars, through fuses *f* for the three voltmeters V at the top of the first panel and through resistances *r* for P. F. I. There is also a voltmeter on one of the phases in parallel with the pilot lamp P L. The remaining apparatus is connected with the excitation circuits of the rotary converter. A lead from the right-hand brush of the commutator is taken to the field ammeter F A, and then to the regulating resistances R. The shunt circuits of the machine are in sections brought to the terminals and switches marked F C, by means of which one or more coils can be cut out of, or brought into, circuit. In addition, the excitation current can be reversed at the reversing switch R S. After passing R S and F C the circuit is completed by passing through the series coil to the left-hand brush. The series coil *s* needs no explanation. The continuous current from the rotary is taken by the leads to the rotary converter panel X (Fig. 534), of the c. c. low-voltage board. The third lead from the left-hand brush of the converter is taken to the contact shown as idle on the switch S (Fig. 534) for connection to an equaliser bar when the rotary is to be paralleled with the main c. c. generators, running at 550 volts.

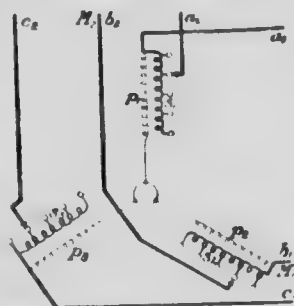


Fig. 540.—Diagram of the Circuits through the Regulator Switch.

Remote Control Boards.—In the early stages of the development of public-supply stations, when the amounts of power and the voltages dealt with at the switchboard were much less than they are in important modern stations, it was possible to design the boards so that all the switches and measuring instruments could be placed on the front of the board in full view of the operator. The possibility of such an arrangement was still further extended when the "panel" system of construction was developed, though the primary object of this system, as explained elsewhere, was different. With the growth of the size of generators the amount of power controlled by a single switch or group of switches increased to such an extent that the switches themselves, re-designed for the new conditions, became massive and elaborate pieces of apparatus which could no longer be mounted on the front of the board. Simultaneously the increase of the voltages of generation, and still more of transmission, required additional safeguards in the design of the switches, which tended towards still

greater increase of size and of the space required for their erection. Still further complications were introduced when the desirability of immersing the break gap for high voltage A. C. circuits in insulating oil was acted upon.

The difficulty was at first met by placing the switches behind the board, where the necessary space could be provided more readily, the switch being manipulated by levers of suitable design. As seen, however, by Ferranti and others, this device did not, and does not, meet all modern requirements, which in large stations now necessitate the still further separation of the switch gear and the section from which the operator in charge controls the whole of the generating and distributing circuits. When this separation is made the personal safety of the operator can be ensured by arranging that none but low-voltage circuits shall be in the neighbourhood of the apparatus which he actually has to handle.

The switch gear at the distant point can be operated in various ways, which may be summarised as follows :—

- (i.) Mechanically, by means of levers, trackers, etc., somewhat similar to those used for operating railway points from signal cabins.
- (ii.) Pneumatically by means of air under pressure operating little air cylinders or engines.
- (iii.) Electrically by electric motors whose circuits are controlled by switches upon the operating board.
- (iv.) Electrically by long-throw solenoid magnets whose circuits also are controlled by switches on the operating board.

By whatever method the distant switches are controlled two essential conditions should be satisfied, viz. :—

- (1) A repeat signal should appear at the operating point to inform the operator whether or not the switch has responded to the movement at the controlling point; and
- (2) The operator at his usual position at the controlling board must be able to ascertain exactly how the actual switch is set at a particular moment.

Mechanical Control.—Even where the amount of power handled is comparatively small, it may be inconvenient, if the voltage is high, to place the main switches immediately behind the operating board or panels. In such cases an adjoining room, if available, may be utilised, the switches being manipulated by levers and trackers, which as explained above, are often similar to the levers used for working railway points or switches.

As an example, Fig. 547 shows the operating section of the Siemens remote control board for the high-voltage generators, synchronous motor, and transformers in the generating station at the Northampton Polytechnic Institute, which will be found described at pages 378 to 381. This

operating section is of the desk pattern, which has been found so convenient in many modern stations. It is placed on a gallery at the generator end of the station, the clock seen in Fig. 395 being on the back of the desk. The operator manipulating the switches in Fig. 547 can therefore see the generators and the synchronous motor which he is controlling; the static transformers, however, are in another room.

The section consists of four panels; on the extreme left are generator panels, one for each alternator (see Fig. 549), next is the synchronous motor panel for the motor generator set seen on the left of the generators in Fig. 396, and at the right-hand end of the section is the transformer panel. The four main switches for these panels are mechanically operated by the handles *H*, the switches themselves, shown in Fig. 543, being in the room immediately behind the operator as he stands facing the board. The switches and the whole of the high-voltage gear are mounted in cells built of artificial stone slabs, the front of the cells being closed with expanded metal screens not shown in Fig. 548.

The deflectional instruments proper to each panel are recessed in the marble of the panel, their dials being flush with the face of the panel, whilst the recording instruments are on the vertical front of the panels. The voltmeter and synchroniser are mounted on a swing bracket at the end



Fig. 547.—Remote Control "Desk" Pattern Operating Board, Northampton Polytechnic Institute.

of the desk, and can be thrown into circuit by suitable plug switches on each panel. The currents in all these instruments are low-voltage currents obtained from the instrument transformers which can be seen mounted in the high-voltage cells of Fig. 548.

The connections for one of the generator panels and for the synchronous motor and the transformer panels are shown in Fig. 549. Taking the generator panel first, the generator itself is shown in the diagram at G, with its armature and field circuits distinct. For the latter a pair of



Fig. 548.—High-Voltage Switches at the Northampton Polytechnic Institute.

leads cc from the busbars of the continuous current low-voltage generator and battery board already described are brought to a double-pole switch placed on the vertical front of the desk, which, when closed, places the field coil of the alternator and the controlling rheostat in simple series on the busbars through a field ammeter, the dial of which is on the face of the desk. It should be noted that, in connection with this D.P. switch, there is a discharging—or, as it is often called, a “kicking”—resistance, which is thrown in parallel with the field coil on the first motion of the switch handle for breaking the field circuit, and before the field circuit is opened. This, as explained elsewhere, abolishes the heavy spark which would result if a circuit so highly inductive were opened suddenly.

The three-phase armature circuits at G₁ are shown connected up in

"star" grouping in the diagram, but can be connected up in "delta" at the machine when so required. In either case, the leads from the machine are carried through fuses, direct to the incoming contacts of the oil switches, shown in Fig. 549. When these contacts are closed by moving the lever in front of the desk, the circuits are continued to the three 2,200-volt busbars, each of which is carried on porcelain insulators in a separate trough placed along the top of the switch chambers shown in Fig. 548. It should be explained here that the levers *L* shown close up to the busbars in the diagrams are not switches, but only links, which are to be opened or closed only when the busbars are dead. Their object is to make it possible to remove a switch and all its connections entirely from the high-voltage

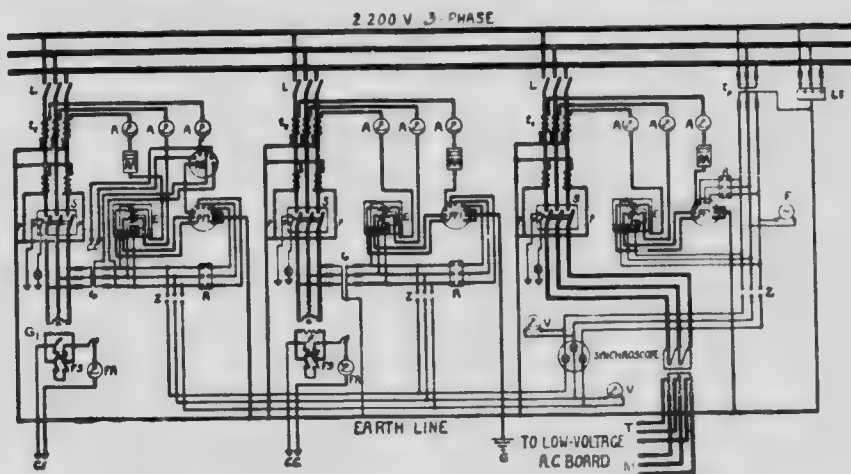


Fig. 549.—Diagram of the Connections of the "Desk"-Pattern Operating Board.

busbars for cleaning or other purposes. Circuits are taken off the mains on their way to the busbars from the oil switch for the primaries of potential transformers, and the main leads pass through the primaries of two sets of current transformers. The first of these, shown in the diagram above the main switch *S*, are on two leads only; their secondaries are to supply current to the tripping coils of the oil switches, which are indicated diagrammatically by two solenoids, one on either side of the main switch levers. These are over-load coils, whose armatures only trip and open the switch when the current in either of them exceeds a certain pre-arranged value. The second set of current transformers *I*, nearer the busbars has secondaries, star-connected, and with the common point of the star earthed, the "earth line" being shown at the bottom of the diagram. These secondaries pass through the three ammeters *A* shown in the diagram, and whose dials appear on the top of the desk. In series

with two of these ammeters there are the current coils of an energy meter *E*, mounted on the vertical front of the desk, and with one of them the coil of a recording ammeter *RA* is also in series. This recorder is also mounted on the front of the desk. The remaining ammeter is in series with the current coil of the reverse relay *RR*, whose function is to trip the main oil switch if the direction of the flow of energy is reversed and the generator is being driven as a motor. The tripping circuit which is energised by continuous currents is represented as leaving the board at *cc*. The secondaries of the potential transformers, *t_p*, which with the primaries are protected by fuses, supply current to the volt-coils of the energy meter *E* and the reverse relay *RR*. All these circuits are in parallel with one another. They are also connected to the contacts of the plug receptacle *z* by which they are put in parallel with the station voltmeters *v* (on two phases) and the coils of the synchroscope, these instruments being shown on the right of the diagram in Fig. 549 joined in parallel to the other contacts of the plug receptacles *z* at each panel. It will be remembered (see above) that the instruments themselves are on swinging brackets over the left-hand end of the desk. The power-factor indicator, *PFI*, which is also on a bracket at the end of the desk receives volt-currents from the same secondaries through another plug receptacle *R*, as shown in the diagram.

The synchronous motor panel of the remote control desk shown in the middle of the diagram (Fig. 549), is connected up in almost identically the same way as one of the generator panels, the chief difference being that the reverse energy relay and its connections are omitted as not being required. Another difference is that the excitation current *cc* is taken from the busbars of the 110-volt panels of the low-voltage *c.c.* feeder board (Fig. 534), instead of from the 220-volt busbars of the *c.c.* generator and battery board. This alternate current motor is run up to the synchronous speed from the panel (Fig. 532) of the 25-kilowatt generator of the set, the generator being used for this purpose temporarily as a motor, the starting appliances for which are on the panel named. When the synchronous speed has been attained its fields are excited and it is paralleled on to the busbars in the usual way.

The transformer panel of the desk control board deals only with the high-voltage circuits of the transformers, the low-voltage circuits being dealt with on the low-voltage *A.C.* board (see Figs. 535 and 545). The transformers *T* are three separate single-phase transformers with their high-voltage coils connected in delta (Δ), and the panel is concerned only with their connections to the high-voltage busbars. As in the last case, it must be remembered that the energy is flowing *from* the busbars to the transformers. The current transformers *t_c* for the instruments are, as in the other cases, placed between the busbars and the main oil switch, but the potential transformers *t_p* have their primaries connected directly to the busbars in-

stead of to the main leads. The secondaries of these transformers feed the volt circuits of the instruments as in the other panels, and in addition the frequency indicator *F* is connected across one of their phases, thus showing the frequency of the currents on the busbars whenever they are live. A leakage indicator (L.I.) is also shown in the diagram with its circuits connected to the busbars through fuses, the other side being connected to the earth bar, to which the neutral points of the secondaries of all the instrument transformers are joined, thus ensuring that the absolute potential of all these circuits shall be low, and securing the personal safety of the operator. It may be noted that two sets of three-phase leads, one of which is at 60 volts and the other at 350 volts, proceed from the secondaries of the large transformers *T*; the reasons for this are given in the description of the A. C. regulating board on page 542.

Electrical Control.—Where the main switches are operated by electric motors or long-throw solenoid magnets energised by currents whose circuits are opened or closed at the control board there is no limit, except that of

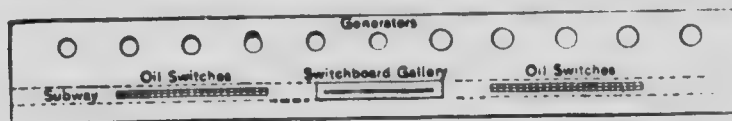


Fig. 550.—Floor Plan of the Niagara Falls Power Company's No. 2 Station.

convenience, in regard to the relative positions of the control board and the switches.

In this connection it will be convenient to set forth first the general arrangement of a modern power house in which such remote control is employed. For this purpose Fig. 550 shows in the barest outline the general floor plan of No. 2 station at Niagara, which has been more fully referred to elsewhere (see page 492). It will be seen that the eleven large generators are arranged in a single row down one side of the station, and that the remote control switchboard occupies a central position on the other side. The switchboard is flanked on either side by the oil switches, and a subway runs the whole length of the station for the necessary connections, cables, circuits, etc. The switchboard itself is on a gallery, and its general appearance and arrangement can be inferred from Fig. 551, which shows it in elevation. The panelled chambers below the gallery contain the recording instruments and other apparatus. In the middle of the board are two interconnector panels *I* for linking together or separating the sets of busbars which are indicated by horizontal lines. The instruments on these panels are ammeters only. The interconnector panels are flanked on the right by six generator panels *G*₁, and on the left by five generator panels *G*₂; each panel carries, besides the switches, two ammeters, two voltmeters, two wattmeters, and a field ammeter. It should be noted here that the system is a

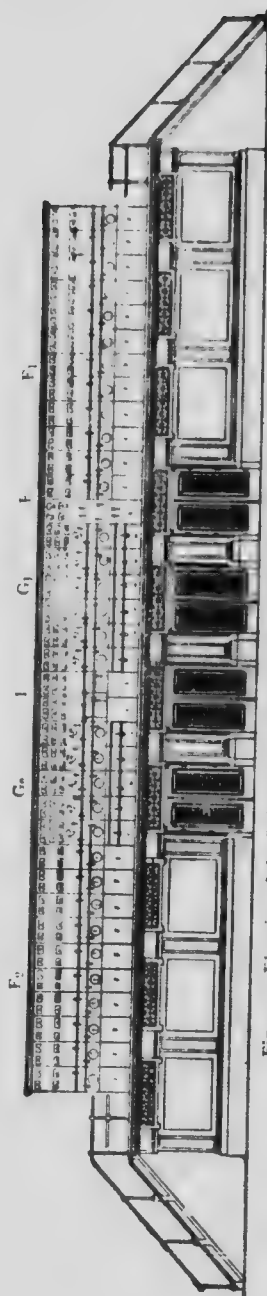


Fig. 551.—Elevation of the Switchboard Gallery at the Niagara Falls Power Company's No. 2 Station

two-phase one. On the right of the generator panels is the exciter panel *E*, the board being completed by twelve feeder panels *F*₁ on the right, and ten similar panels *F*₂ on the left. Each feeder panel carries two ammeters and two wattmeters, and on each of the eleven generator panels and the twenty-two feeder panels there is a time-limit relay.

It will be understood from the above that the actual positions of the various main sections of the apparatus may be arranged as may be most convenient to the particular circumstances of the site or building. In the example just given they are all in one room, but this is not essential, and in some modern stations the control board is in a room or even a building quite separate from that which contains the generators. It is, however, obvious that the main switches carrying full load currents are most conveniently placed near the generators, and the outgoing feeders.

The Niagara switchboard had its control switches and instruments arranged on vertical panels, but the "desk" type adopted for the "Northampton" board (Fig. 547) is widely used, and another example of it is therefore shown in Fig. 552, which depicts a twenty-panel board manufactured by the British Westinghouse Electric and Manufacturing Company, and erected at the Bahia Blanca Power Station. It controls five 1,000-kilowatt steam-driven alternators generating three-phase current at 6,600 volts, and 50 ω . Counting from right to left the board consists of five generator panels, one interconnector panel, two transformer panels, and twelve feeder panels. Each panel carries its own special instruments, lamps, etc., the instruments mounted at the back being common to more than one panel.

A diagrammatic elevation of one of the generator panels is given in Fig. 553, and a cross-section of the board at one of these panels is given in Fig. 554. In the elevation (Fig. 553)

the small rectangle at the top represents the low vertical back, carrying only the pilot lamps in two pairs coloured blue and orange respectively. These lamps are connected through instrument transformers to the high-voltage busbars, of which there are two sets, one pair being connected in parallel to each set and two lamps being used to guard against breakages of the filament or other causes of failure.

The middle rectangle shows the positions of the apparatus on the sloping part of the desk. The three measuring instruments are an ammeter *A*, a wattmeter *W*, and a power factor indicator *P.F.* Below the instruments are three indicating lamps showing red, green, and white respectively. The red lamp lights when the main switch is closed, the green lamp lights when the switch trips automatically, and the white lamp lights when the switch is altogether out of circuit.

At the front of the desk below the three lamps is the levers of the small control

switch which operates the distant main switch of the generator. The connections are made on a small cylindric controller, similar to the large controllers used for other purposes, placed below the surface of the desk as shown in Fig. 554, the oil switch controlled being of the type fully described

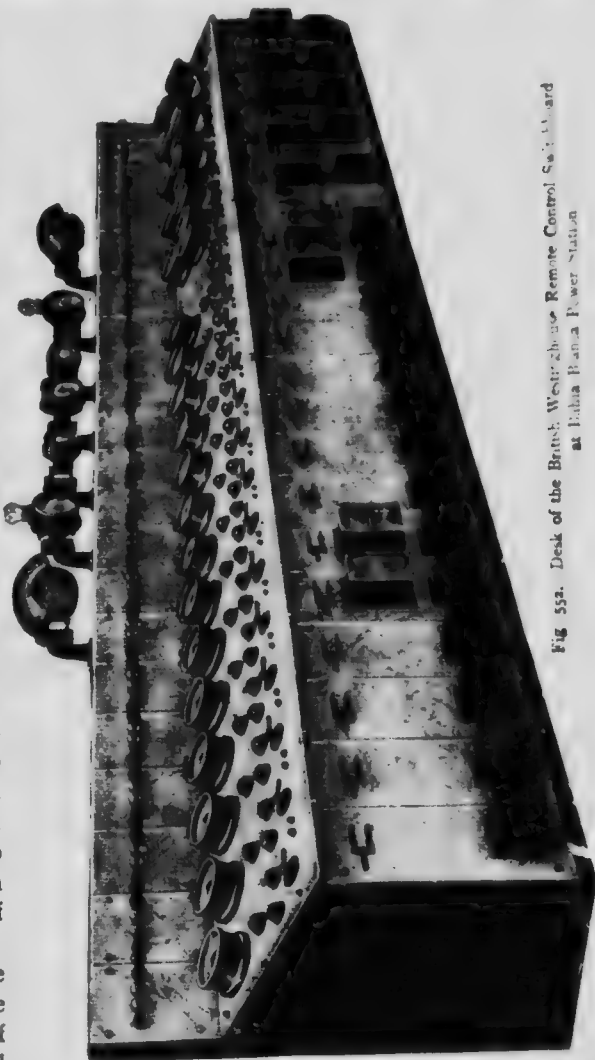


Fig. 552. Desk of the British Westinghouse Remote Control Switchboard at India Point Power Station

on page 570. The controller has three positions; a movement of the lever to the left closes the circuit of the "closing coil" (Fig. 567), and the switch closes; simultaneously the red lamp on the desk lights. If the lever is

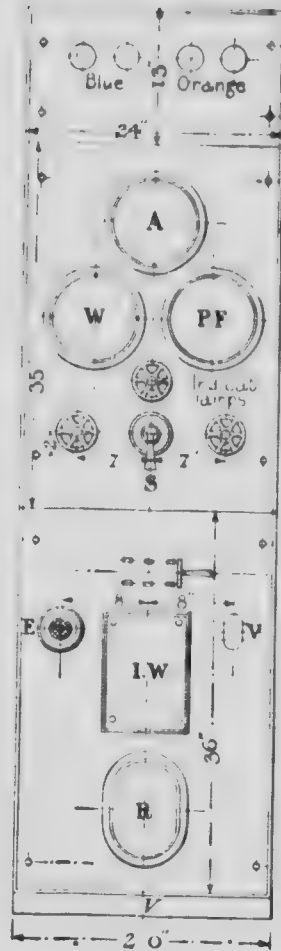


Fig. 553.—Elevation.

One Panel of the Westinghouse Remote Control Desk at Bahia Blanca.

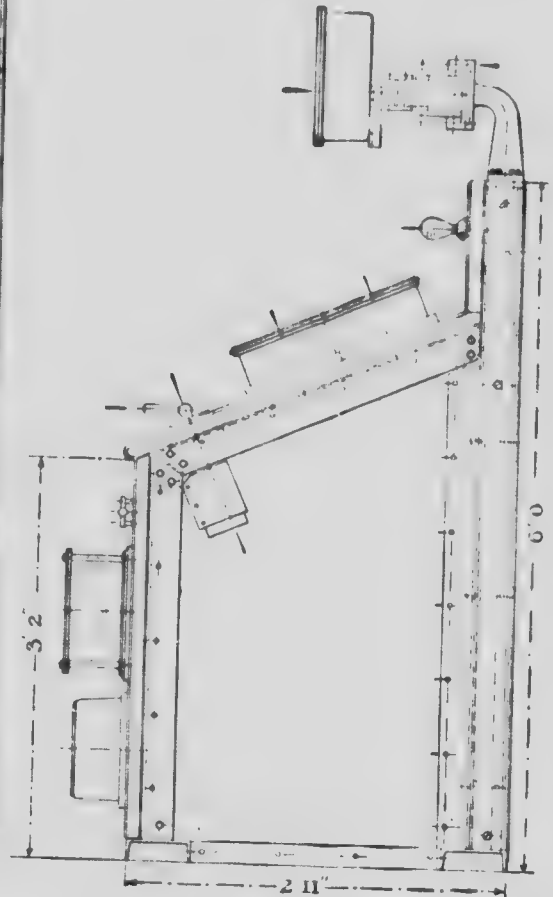


Fig. 554.—Cross-Section.

now released it springs back to the "off" position and nothing happens. On moving the lever to the right the circuit of the tripping or "opening coil" (Fig. 567) is closed, the tripping mechanism operates and the switch opens. This coil is also excited in the event of an overload occurring or if it be attempted to close the main switch against an overload.

The front of the desk carries at the top a small double-pole double-throw switch which takes the place of synchronising receptacles in other patterns of boards. As already explained there are two sets of busbars; for synchronising purposes each has its own instruments, which can be seen in Fig. 552, mounted at the top of the board. These instruments from left to right are (i.) a busbar voltmeter, (ii.) a synchroscope including two synchronising lamps, (iii.) a frequency meter, and (iv.) an incoming voltmeter, the first three being then duplicated for the second set of busbars. The small switch referred to above is to enable the operator to synchronise his incoming generator with either set of busbars.

Similar small switches appear at the top of the feeder panels where they are not required for synchronising. The switches there are used for throwing over the pressure coils of the indicating wattmeters on these panels from one set of busbars to the other.

Returning to the generator panel (Fig. 553) we have below the D. P. switch an integrating wattmeter or energy meter *W*, and below this again a reverse energy relay *R*, which will trip the main switch if the generator begins to act as a motor. On the right and left of the energy meter there are a voltmeter receptacle *V* and an engine governor switch *E*.

On the feeder panels the single instrument on the slope of the desk is a wattmeter, and the instrument at the bottom of the vertical front is an overload time-limit relay. In addition an energy meter is mounted on the front of the fifth, and another on the front of the sixth panel.

At the end of the twelve feeder panels there are two transformer panels which call for no special remark, and between them and the first generator panel there is an interconnector panel for connecting together or for disconnecting from one another the two sets of busbars.

Ferranti High-Voltage Remote-Control Board.—Mr. Ferranti, who has done so much in other directions for the development of electrical engineering, has been a pioneer in the development of switchboards, especially for high-voltage work. The leading principle, which he has insisted upon from the commencement, has been the isolation of every part of the switchboard in separate cells wherever there are high-voltage currents. The separation for the highest voltages is made by means of brick walls and concrete floors and sides to the various cells in which the different parts of the apparatus are assembled, these cells being closed in front by removable iron or other screens. Only low voltage circuits from the instrument transformers and the low-voltage circuits for energising the operating magnets of the large oil switches are on the operating board, so that the operator is in no danger of coming directly into contact with high-voltage circuits. As a further protection all metal parts of the operating board which are not in circuit are carefully earthed.

Another principle insisted upon is that the back of the operating board

shall not be close up against a wall, making it difficult, if not impossible, to get at the connections for inspection and repairs without taking down the board. Mr. Ferranti has always insisted that the switchboards should

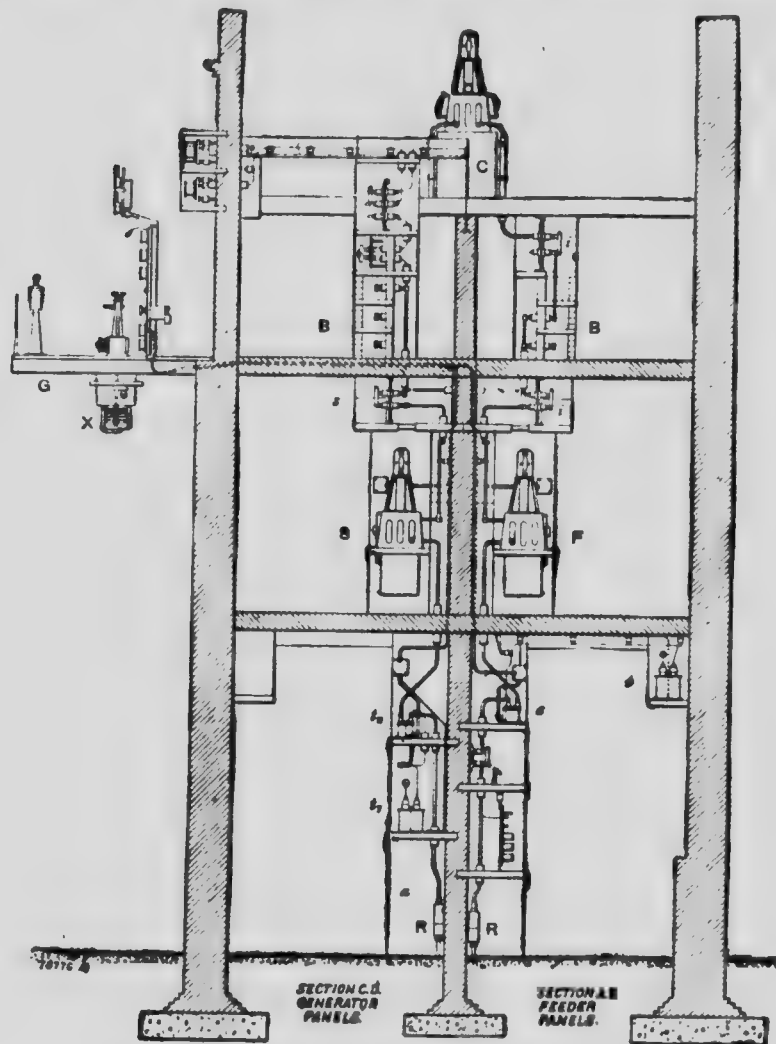


Fig. 555.—Vertical Section of the Ferranti High-Voltage Switchboard.

be "backless" and that there should be ample space behind for working safely there under all possible contingencies. For many years now all first-class boards have been constructed on this principle.

As an example of one of the latest patterns of high-voltage alternate current switchboards we shall now describe in detail the Ferranti board erected at the St. Andrew's Cross station of the Glasgow Corporation for the control of six three-phase turbo-generators each of 3,000 kilowatts output at 6,500 volts and 25 periods per second. The exciter for each generator is mounted on the turbine shaft, the current supplied to the field magnets of the alternator being controlled by a variable resistance in the field circuit of the exciter adjusted at the switchboard. The operator has

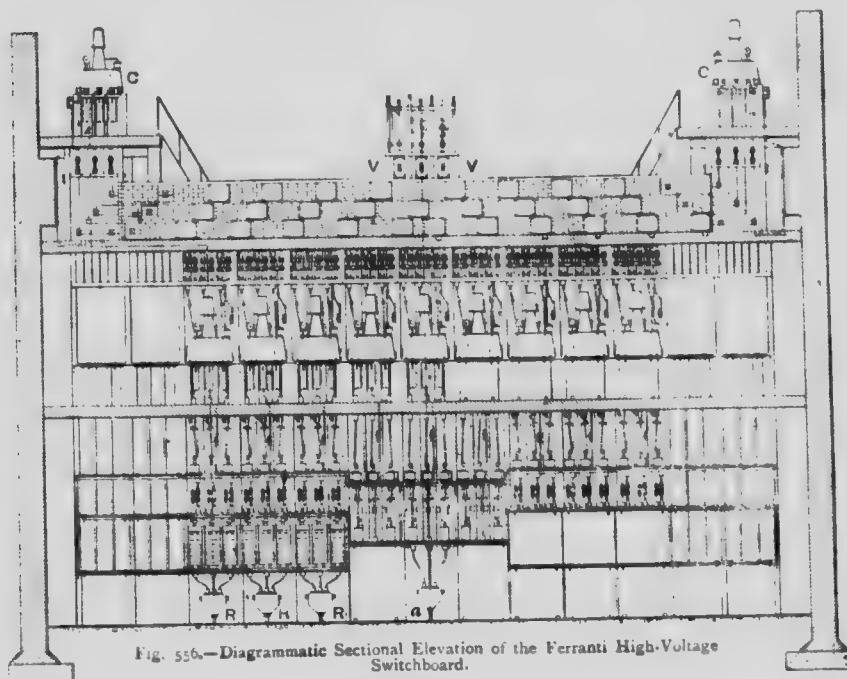


Fig. 556.—Diagrammatic Sectional Elevation of the Ferranti High-Voltage Switchboard.

further to direct the current to eighteen feeders and to two inter-connector circuits which are operated from the board.

With these objects to be attained the board designed is shown in cross-sectional elevation in Fig. 555, and in front elevation in Fig. 556, with certain details inserted diagrammatically. The board is in three storeys supported by two main and one intermediate vertical walls with cross floors for the different galleries. The main wall on the engine room side carries the operating gallery *G*, Fig. 555, on brackets, at the second storey level, and the intermediate wall carries the main oil-switches on the first floor, and the various instrument transformers, busbars, etc. The board is 50 feet wide between the vertical walls in Fig. 556.

As there are six generators, eighteen feeders, and two interconnectors the board is divided into twenty-six panels, thirteen on the front and thirteen on the back. The busbars *B B*, Fig. 555, lie at the back and the front of the intermediate wall, and are in two sets, which can be joined together by the connector switches *c c* at the ends. The six generator panels are in the centre, three (Fig. 556) on each side of the wall, and the

remaining twenty panels are in two flanking sets of five each.

The appearance of one side of the lowest or ground floor gallery is shown in Fig. 557. The busbars themselves are enclosed in chambers which are illustrated in Fig. 558, and are placed in a gallery from which access can be had to them when necessary through the iron doors shown at intervals, the doors being opposite the insulators which are carrying the bars.

Turning now to the vertical section (Fig. 555), the best plan will be to

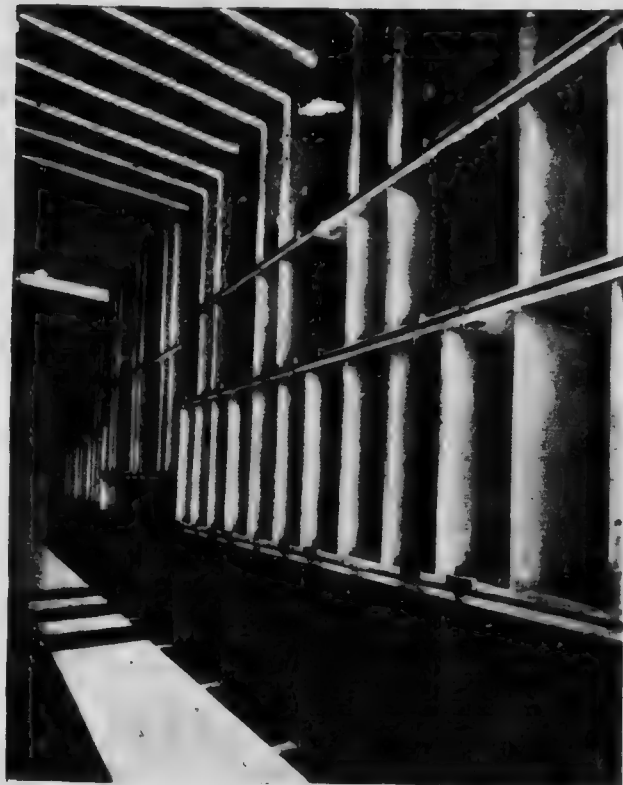


Fig. 557.—Lower Switch Gallery of the Ferranti High-Voltage Switchboard.

track out the course of the current coming into one of the generator panels from the bottom upwards. The three-core cable from the generator is brought first into the lower cell *a* of the switchboard to a trifurcating head *R* at which the three cores are separated from one another and pursue their paths through the board as three single cables. Immediately above the trifurcating cell, and separated from it by a horizontal concrete or other insulating slab, cells *t₁*, *t₂* are provided for the voltmeter transformers and for the series transformers for the ammeters on the operating

board. There are separate cells for each type, the voltmeter transformers being in the lower compartment (t_1), and the series transformers in the upper compartment (t_2). The secondaries from the series transformers are taken to a terminal board, and the whole of the secondary leads for a single generator are carried by a specially designed low-pressure cable to the operating board. Thus, for measuring purposes the voltmeter currents and the ammeter currents which leave these cells are passed on to the operating board at a low voltage.

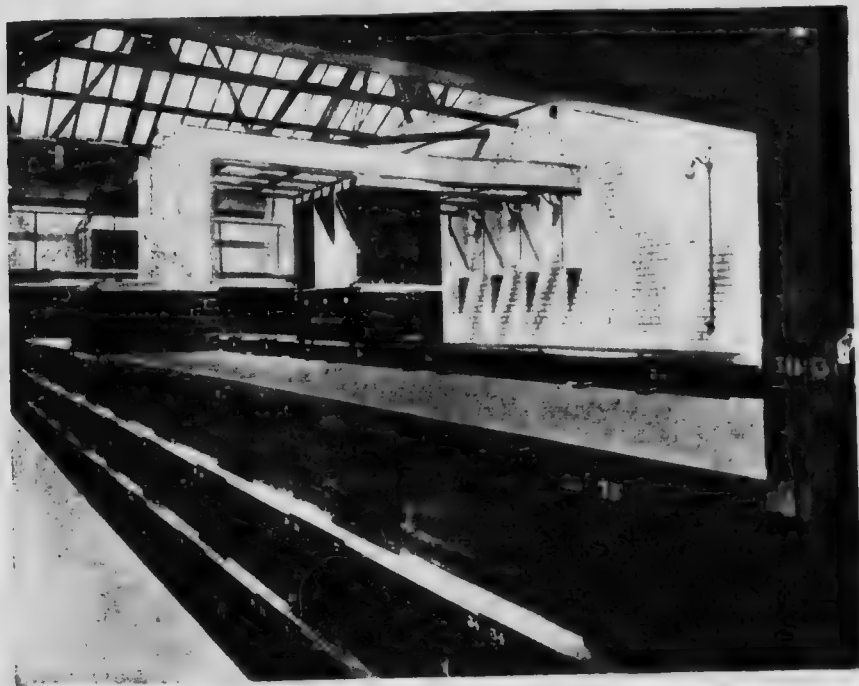


Fig. 558.—Busbar Gallery of the Ferranti High-Voltage Switchboard.

The main leads pass up next into a large cell above (Fig. 555), containing the main switches, from which they pass to a little compartment above in the same gallery and containing the selector switches. There is thus minute subdivision, both horizontal and vertical, at each step, even the selector switches being in a sub-cell, as it were, by themselves. From these the current can be directed either to the back busbars or the front busbars. The selector switches are not opened or closed from the operating board at all, and are never to be touched except when the switch is dead. They are knife switches, operated with a long pole, by which they can be opened or closed. According to the selector switch used the cur-

rent passes to the front busbars or the back busbars B B, each busbar being in a separate cell as already described. The three busbars cannot spark to one another, the partitions between them being both horizontal and vertical; the appearance of the busbar gallery is shown in Fig. 557 which is reproduced from a photograph.

In the centre of the board above the busbars there are special cells *x*, Fig. 556, containing cut-outs for electrostatic voltmeters, the wires from these cells passing first to selector switches above, and then direct to the electrostatic station voltmeters fixed on the wall behind, but not on the operating board (see Fig. 559). These voltmeters therefore measure the voltage of the busbars.

At either end the busbars turn at right angles and pass to isolating switches similar to the *e* previously described, but interposed between the busbars and the connector switches by which the two sets of busbars can be joined in parallel when so required.

The other half-section on the right in Fig. 555 shows the outgoing feeders. Starting from the top just below the busbars there are isolating links or switches *i i* which act as selector switches to direct the current from either set of busbars to a particular feeder. Below the selector switches is the switch proper, that is the feeder switch *f*, an oil switch similar to the generator switch, and opened and closed from the operating board. Having passed through that, if it be closed the current passes down to the current transformers *c*, and the potential transformers *p*, which are installed in a little cell by themselves on the other wall.

Immediately below the transformer range (see also Fig. 556), are isolating switches, and in the compartment below the static dischargers. The static dischargers are to prevent any surge coming in from lightning or thunder storms, or other disturbances. Finally, in the lowest compartment of all are the cable receivers R R R, Fig. 556, which gather up the leads to the cable head from which they go out to the sub-stations on a three-phase cable. There are, as already explained, eighteen of these feeder runs on the board; the remaining two sections contain the switches and auxiliary apparatus for the inter-connectors of this station with other stations.

The front of the operating board is shown in Fig. 559, obtained from a photograph taken before the board was quite completed, and showing some unfilled blanks. On the near end four feeder panels are chiefly conspicuous, the generator panels being in the middle. The iron pedestal immediately in front of each generator panel supports a hand wheel for working the exciter rheostat of the generator. The rheostat *x*, Fig. 555, is a low-voltage rheostat, and is suspended just below the column from the under-side of the platform. The gears of the six rheostats are so connected one with the other that by working one of the handles the exciting currents for the whole station can be increased or diminished. Thus if it

It is desirable to raise or lower the excitation of the whole station it can be done by working one handle only. If, however, it is desired to alter the voltage of a single machine only, the connecting gearing can be thrown out and that rheostat worked by itself. At the base of the pedestal there is a double-pole throw-over switch with non-inductive resistance in the exciter circuit.



Fig. 559.—Operating Board of the Ferranti High-Voltage Switchboard.

On the vertical panel, which is 2 feet wide, the three instruments at the bottom are the reverse current or, more properly speaking, the reverse energy relays worked by the low-voltage currents of the instrument transformers. Above these is the hand wheel of the main switch, the operation of which will be described presently (see page 567), and immediately above it the receptacles for the voltmeter switch and for the synchronising connections. Then come the pilot lamps, showing whether the switch is open or closed, and higher up are the generator measuring

instruments, consisting of one ammeter and one voltmeter, the voltmeter reading up to 10,000 volts and the ammeter to 500 amperes; there is also a power-factor indicator and a deflectional wattmeter, the wattmeter reading up to 4,000 watts. All these instruments are, of course, worked by low-voltage currents from the secondaries of the instrument transformer referred to above. Lastly there is a field ammeter and a field voltmeter which are right in front of the operator as he manipulates the hand wheel of the exciter rheostat.

Of course the generator instruments are on the generator side of the switch, the station voltmeters on the back wall being on the busbar side. The columns on the front of the gallery are ship's telegraphs for signalling to the engineers in charge of the engines.

The feeder panels shown on the right of Fig. 559, are quite simple. Beginning at the top there is first an ammeter upon one phase of the feeder only, then an energy meter, below which are the pilot signals and the hand wheel for the main switch. At the bottom there is a three-pole overload relay, one pole upon each feeder, so that if any phase of the feeder gets over-loaded the switch is automatically opened. The circuits of this overload relay, and of the other instruments are of course taken from the secondaries of the instrument transformers.

The two panels between the feeder panels and the generator panels are two inter-connector panels. They contain the necessary switches, instruments and synchronising apparatus for connecting up with the other stations on the system. The busbar couplers are on a panel just below the voltmeter brackets; it carries only the operating wheels and pilot lamps for the two switches. The synchronising voltmeters and synchroscopes are mounted on swinging brackets, so that they may be turned towards the operator when required.

The appearance of the back of the operating board is given in Fig. 560, which shows, in the order named, the four-feeder panels, the two inter-connector panels, and the three generator panels, which are shown at the near end of the board in Fig. 559; it is not possible, and would serve no useful purpose, to follow out the details of the wiring shown in the figure, but it is of interest to note that Mr. Ferranti brings the low-pressure leads from the instrument transformers of each section of the board to the operating board by conductors carried in a single cable specially designed for the particular set of leads, instead of running separate wires for each of those leads. The operation of wiring is thus simplified, minimising the risk of error.

Although, however, it is unnecessary to go through the details of the wiring a brief description of the method of operating the main switch and of the operating circuits will be of interest and is important. Of the two chief methods of working large switches by electric remote control, Mr. Ferranti has adopted the solenoid method. The switch used will be described

presently (see page 567); the connections of the control circuit are given in Fig. 561. The continuous current for working the switch is obtained from the battery. At the board the method of operation is to turn the hand wheel as far as possible in the right-hand direction; this winds up a spring, and nothing further happens just then. On the spindle of the hand wheel there is a barrel like the barrel of a cylindric controller for motors, but much simpler, carrying only the four vertical bands shown

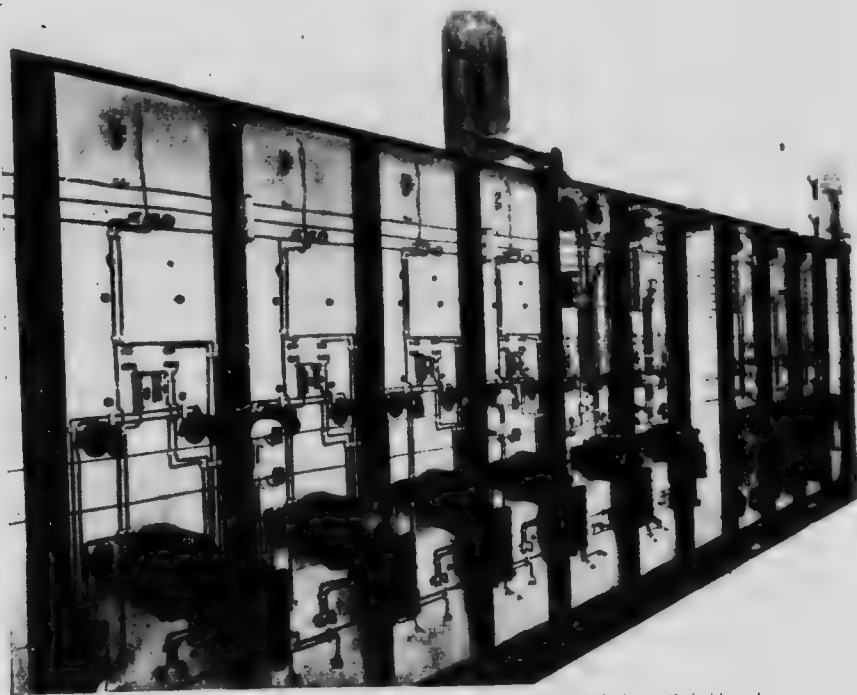


Fig. 560.—Back of the Operating Board of the Ferranti High-Voltage Switchboard

at *c* in Fig. 561, and making contact in certain positions with the leads opposite them shown by the fine lines. As the hand wheel is revolved the controller cylinder is kept from rotating by a ratchet, and the contacts remain open. Assuming that a generator is to be thrown into circuit the synchronising apparatus is, of course, being used, and when the synchronising moment comes, by touching a button the ratchet is released and the controller cylinder revolves.

Ring *a* (Fig. 561) of the controller is then connected through the fuse *F* to the positive terminal of the battery, and through the ring *b* the current is passed through a resistance *R* to the operating coil *o* of the switch solenoid, thus closing the switch. The resistance *D*₁ is a non-inductive resistance

bridged across the solenoid to discharge its energy when the circuit is opened. The circuit is completed through the two controller contacts *c* and *d* on the right through another fuse to the negative pole of the battery. Thus when the controller barrel is released the operating coil *o* receives current, and the switch is closed. On being closed the switch is held closed by a catch which must be released or "tripped" before the switch can be opened. In the last position of the controller barrel at the end of its rotation the contacts are again opened and the solenoid *o* is left inert.

The rest of the circuits are for the tripping coil. First of all the negative pole of the battery is connected to a three-way switch *P*₂, through the fuses *D* and the lamps *L*. That switch is placed in the "off" position when the main switch is open and in the "on" position when the main switch is closed. When the switch is "on" (main switch closed) the tripping coil marked *T*, shunted with its discharge resistance *D*₂, can be put into circuit at any of the points *R*₁, *R*₂, *R*₃, or *P*₁. At *R*₁, *R*₂, and *R*₃, are the overload relays, worked by the currents in each phase respectively. When an excessive current is developed on any phase, the relay operates and closes

the circuit, sending a current through the tripping coil, releasing the catch, and opening the main switch. The fourth point *P*₁ represents a press button on the other side of the hand wheel on the operating board,

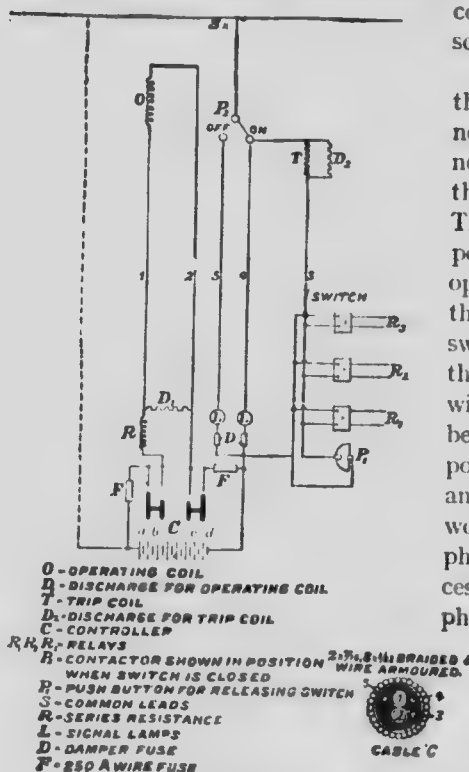


Fig 561.—Diagram of Circuits Controlling Ferranti-Field Oil Switch.

which when pressed trips the catch and opens the switch from the switchboard. This main switch therefore, by the action of the relays, acts as an automatic circuit breaker. The lamps *L*, Fig. 561, are the pilot lamps on the operating panel, and according to the position of *P*₂, one or other, but not both, lights.

It might be well here to point out what are the requirements of such operations as we have just been describing. Rapid action at the main switch is essential, and that rapid action should be independent of the

personality and idiosyncrasies of the operator. It is well known how nervous some people are at critical moments, and such must occur when synchronising a large alternator, and especially when just on the point of throwing it into circuit. Thus the arrangement, whatever it is, must be independent of the operator; when he has made his final touch and started the movement, everything must go through its prearranged course at the prearranged rate, with no chance of interference.

Slow breaking is especially to be avoided, because if the switch hangs there may be a very dangerous arc. Thus in the example just given the movement of the hand wheel winds up a spring, which, when let go, revolves the controller barrel, and the controller contacts at a definite speed. A dashpot attached to the barrel gives the breaking just necessary for the solenoid electro-magnet to build and do its work before the operating circuits are finally opened again on the completion of the cycle of operations.

Oil Switches.—It was originally intended to conclude this chapter with a fairly complete account of the leading types of switches, relays, and circuit breakers used in large switchboards, the measuring instruments being dealt with in a separate chapter. Considerations of space will not, however, allow this plan to be carried into effect, but, as the most interesting of this class of apparatus, some reference will be made to the large oil switches which play such an important part in modern high-voltage work.

The dangerous and persistent arc which may be formed when a high-voltage circuit is opened in air very early led to special devices being invented to deal with the difficulty. One of the earliest of these consisted in making the break excessively long, say four feet and upwards. It was, however, known that if an arc were struck in insulating oil, instead of in insulating air, a higher voltage was required to maintain it. In other words the disruptive strength of such oils is much higher than ordinary air, and a shorter gap will be sufficient to kill the arc, if any, formed on breaking a given circuit. This led to the invention and development of the so-called oil switch, which is simply a switch so designed that the break gaps, which it can introduce into a circuit are formed in positions immersed in a suitable insulating oil.

The switches, can, of course, be operated directly or by any of the methods of remote control already alluded to (see page 548). For our present purpose it will suffice to describe two or three examples of oil switches operated electrically by remote-control devices.

The Ferranti-Field Switch.—In describing the large Ferranti switchboard (see page 557 *et seq.*) allusion has been made to the oil switches used on the main currents, and the method of operating these switches has been given; incidentally some of the requirements which should be fulfilled by such a switch have been mentioned. A row of switch cells on this board is shown in Fig. 562, in which a part of the mechanism operating

one of the cells can be seen. The acting agent is a long-pull solenoid magnet which was designed by Mr. M. B. Field. It is known as the Ferranti-Field switch, and can be seen in the figure mounted above the switch. A better idea of the details of the switch will be obtained from Figs. 563 to 565. Of these Fig. 563 is a drawing partly in section, showing the solenoid, tripping mechanism, etc., whilst Fig. 564 is a side view of the whole of the switch as seen from the left-hand side of Fig. 563. It will be understood that the func-

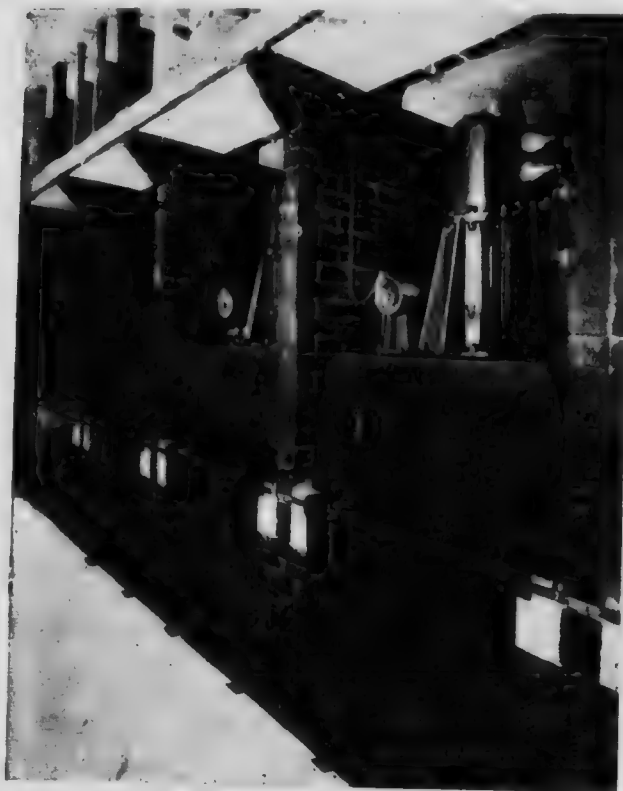


Fig. 562.—Ferranti-Field Oil Switches Installed.

tion of the solenoid is to lift vertically and simultaneously the bridge pieces, not shown in either figure, of each of the three phases and to bring and hold them in contact against the fixed electrodes or contacts on each pair of leads which are to be connected. A bridge piece connecting one pair of electrodes is shown separately in Fig. 565, and will be referred to later.

The solenoid is an ironclad electromagnet energised by two coils c.c., which are shown connected in parallel to the terminals by which they will be joined up to the control circuit (Fig. 561). The plunger, which is shown in its highest position, is not solid, but consists of two thin concentric iron tubes separated by an air space and each split longitudinally to kill the eddy currents which would otherwise flow in the iron whilst the magnetic flux is being built up. The result is that when the exciting circuit is closed, the growth of the magnetism is practically instantaneous, and the mechanism immediately responds without any lost time, an important point when synchronising. A slipper moving in slides is fixed to the lower

end of the plunger, and this in its turn carries at its corners four pipes p, p ; these pipes at their lower ends are bolted to the framework carrying the contact suspenders s (Fig. 503). This framework is also suspended from the solenoid casing by two long spiral springs x, x (Figs. 503 and 504), which assist the pull of the plunger when the switch is closing.

For the tripping mechanism the slipper above referred to has also attached to it four links L_1, L_1 (Fig. 503) which at their lower end engage with four other links, L_2, L_2 , which move round fixed centres attached to the

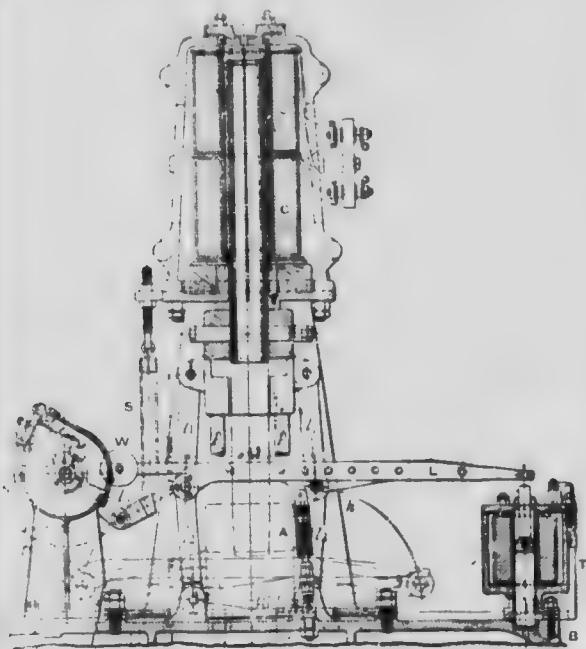


Fig. 503.—Solenoid and Tripping Mechanism of Ferranti-Field Oil Switch.

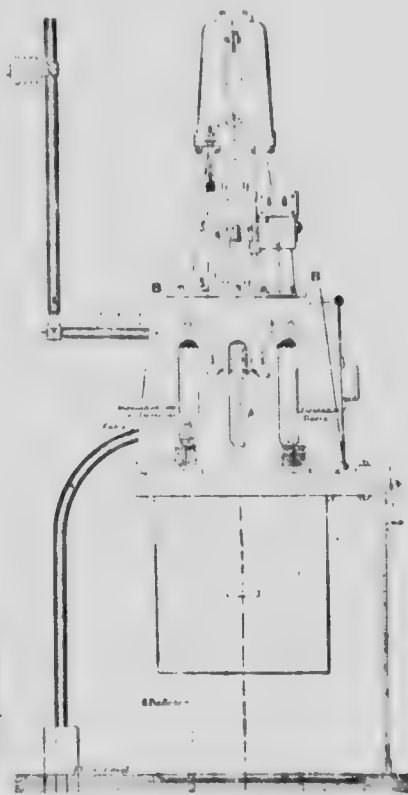


Fig. 504.—The Ferranti-Field Oil Switch End View.

base, B, B . This forms a double toggle mechanism, which when the switch is closed is held stiff by the tripping lever L , which is hinged on the centre pin of the left hand toggle, and carries a catch h which engages with the centre pin of the other toggle. The pressure on this catch is very slight, so that quite a light upward blow on the lever L lifts the catch and allows the links to collapse into the position shown by the dotted lines in Fig. 503. The necessary blow to open the switch can either be given by hand or mechanically, but is usually given by the plunger of the ironclad tripping solenoid T shown on the right hand end of the base. The connections for

this magnet have already been discussed at page 566, Fig. 561. The tripping lever carries a balance weight *w*, and a spring attachment *a*, which ensure the engagement and retention of the catch when the switch closes.

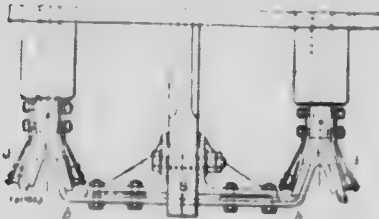


Fig. 565. Contact Jaws and Bridge-Piece of Ferranti Field Oil Switch.

The general result is that when the main solenoid *c c* is excited the bridge-piece *b b* (Fig. 565) is brought up smartly to and held firmly between the contact jaws *J J*, which form the electrodes to be bridged. This bridge piece is a single copper strip fixed to the wooden suspender *s* by a pair of brackets. The fixed contacts *E E* are provided with the contact jaws *J J*, which are flexibly attached to them; each jaw is backed by a strong spring pressing on its centre, ensuring good and even contact and avoiding all possibility of the bridge piece sticking.

In conclusion it may be pointed out that the solenoid plunger has a travel of twelve inches, which is directly transferred to the bridge piece. It is claimed that the mechanism is therefore much simpler than

when multiplying levers are used to increase the effective stroke of a magnet or when an electric motor and gearing are used to close the contacts.

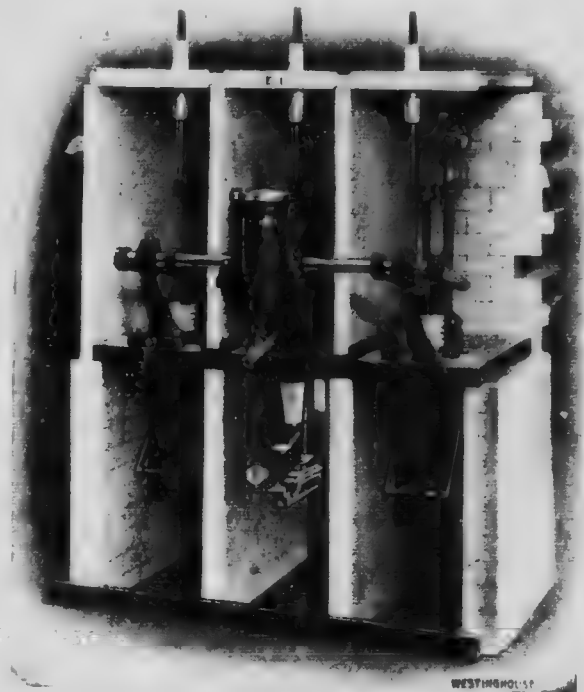


Fig. 566.—Westinghouse Triple-Pole Oil Switch.

The Westinghouse Switch. The standard form of the remote-controlled oil switch manufactured by the British Westinghouse Electric and Manufacturing Company is shown in Fig. 566, which is a view of a triple-pole switch for three-phase working. The three poles are in three separate fireproof cubicles, and the greater part of the operating mechanism is in three other cubicles above the former ones. Into these upper cubicles the incoming and outgoing leads are brought, being very carefully insulated in their passage through the containing walls. The operating magnet with the tripping mechanism is placed in a central position, and acts by rotating the horizontal axle which can be seen supported on brackets in front of the cubicles. This axle actuates the links by which the contact bars *B* are raised and lowered. The oil vessel has been removed from the centre compartment to show the details of the switch.

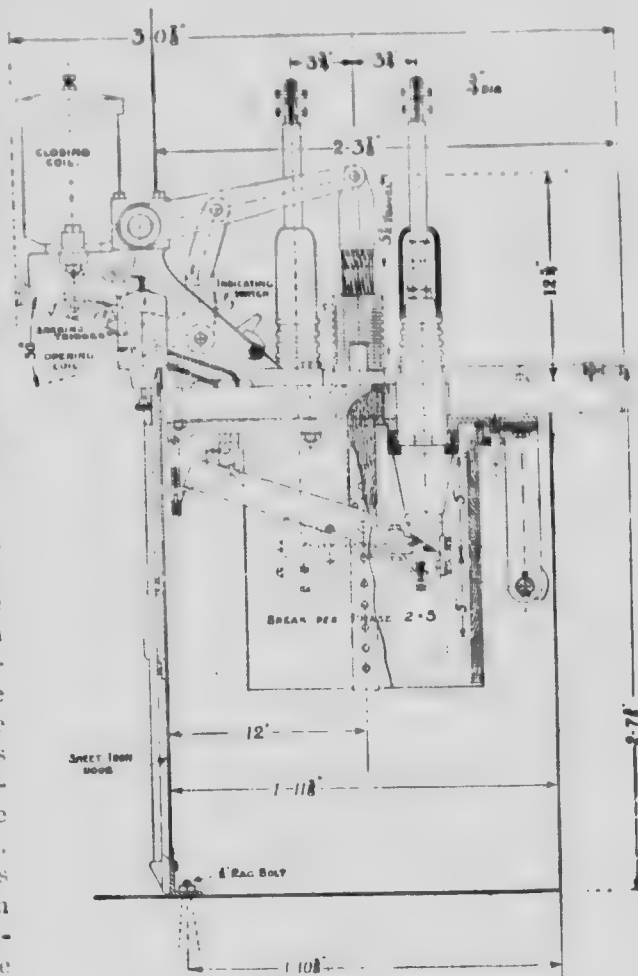


Fig. 567.—Details of Westinghouse Triple-Pole Oil Switch.

The action of the mechanism will be better understood by reference to Fig. 567, which is a drawing of the details, and is also marked with the principal dimensions. In this drawing the switch is shown closed. It will be opened if the tripping coil *a* is energised so that its core is raised and strike

the end *b* of one arm of the bent lever, at the end of the other arm of which the locking trigger is holding the pin *e*, which is fixed to the main operating lever *f*. As soon as the pin *e* is released the switch opens by the collapsing of the toggle joint *t* and the falling of the main operating lever through an arc of about 30° . The vertical part of the switch in falling has a travel of $5\frac{1}{2}$ inches, and cushions on the coiled spring *s*. The switch is closed by the core of the solenoid of the closing coil being drawn up and raising with it the lever *f* until it is again locked by the pin *e* engaging with the locking trigger. It may be noted that the break per phase consists of two gaps each over five inches long.

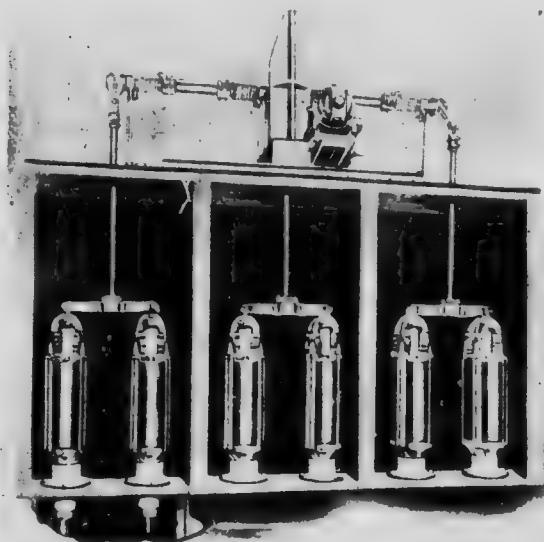


Fig. 568.—General Electric Company's Triple-Pole Oil Switch for 200 Amperes at 15,000 Volts.

British Thomson-Houston Switch.—Without going into so much detail as in the last two cases it is desirable to describe a remote control high-voltage oil switch operated by an electric motor, and for this purpose we select the well-known oil switches of the General Electric Company of New York, represented in this country by the British Thomson-Houston

Company, Ltd. In addition to being motor operated, these switches differ from the two previously described in important general details. A triple-pole single-throw switch with its pairs of poles parallel to the front of the cubicles is shown in Fig. 568, and another with its pairs of poles at right angles to the front of the cubicles is shown in Fig. 569. Each switch is designed to operate at a pressure of 15,000 volts, but whereas that in Fig. 568 is intended to handle currents up to 200 amperes, the switch in Fig. 569 has a maximum capacity of 1,200 amperes. The operating mechanism by which the vertical wooden rods working the contacts are moved up and down is mounted on the top of the cubicles, and in each figure the electric motor can be clearly made out.

The most striking differences between this design and the previous

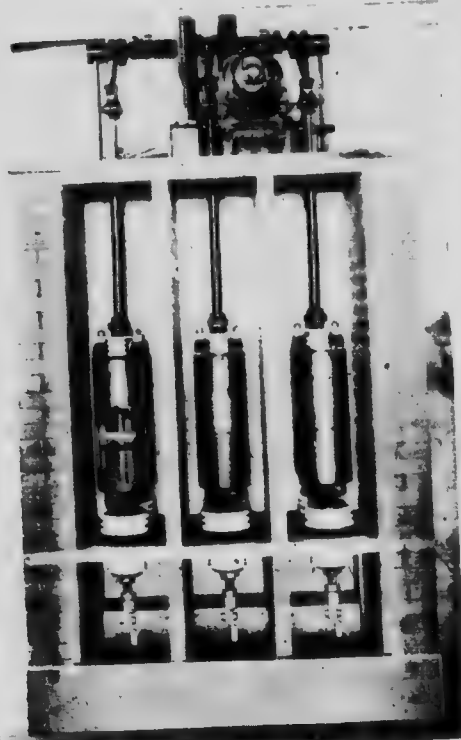


Fig. 569. General Electric Company's Triple-Pole Oil Switch for 1,200 Amperes at 15,000 Volts.

and on a larger scale in Figs. 570 and 571, the socket for the reception of the lower end of the wooden rod being shown in the middle of each cross-head. At each end of the cross-head there is a long metal rod which passes down (Figs. 568 and 569) into an oil pot. The conductors to which contact is to be made are led into the bottom of these oil pots, and the first contact is made at the bottom of the oil vessel by the metal rod entering a

ones are that each break is made in a separate oil pot, and that the current-carrying bridge pieces between the connected electrodes when the switch is closed are not immersed in oil. These bridge pieces are in fact the cross-heads at the bottom of the wooden rods referred to above. They are shown separately for each of the preceding figures



Fig. 570. Primary and Main Contact Pieces of the General Electric Company's Oil Switches.

Fig. 571.

stationary contact consisting of four segments of extruded metal held in place by helical springs. After this contact has been established, and on a further downward movement of the cross-head the brushes (Fig. 57) or fingers (Fig. 57I) make contact with the corresponding fixed contacts at the top of the oil vessel, and become the current-carrying contacts. Vice versa, on opening the switch the contacts at the top of the oil vessel are first opened, but the final break is made in the oil at the bottom of the oil vessel when the metal rod slips out of the stationary contact there.

The switch is closed by the electric motor, which is series wound, acting through worm-and-spur gearing and a friction clutch. The motor is operated by a continuous current controlled at the switchboard, and there are the usual lamp devices for showing whether the switch is fully open or fully closed. The switch can be rapidly opened by trip mechanism, operated either automatically or from the switchboard, bringing into play powerful springs which are compressed during the process of closing the switch.

CHAPTER IV

CONTINUOUS CURRENT MOTORS

THE preceding chapters have dealt fully with the problems connected with the generation of electric energy in the various forms which are either suitable for immediate utilisation or for the transmission of the energy to more or less distant points, where, after proper transformations, it can be usefully employed. It is proposed in this and the immediately following chapters to deal with the technical details of some plant and apparatus required in, and the problems connected with, the utilisation of electric power, leaving over for later chapters the problems of transmission and transformation. The nature of the problems thus postponed and the general methods available for their solution have, however, already been referred to in Volume I. (see Chapters XI. (v.), XV., and XVII.) and the technical aspects of some of them will be better appreciated after the consideration of the design, construction and methods of working of the various types of electric motors whose development has largely contributed to the utilisation of electric power for the service of man in so many directions.

INTRODUCTORY

In the historical volume the elementary principles and chief lines of development of continuous current motors have been briefly sketched, and in the chapter on continuous current generators the details of design which apply equally to generators and motors have been described. In this chapter it is intended to deal with some of the details of design and construction in which continuous current motors differ from generators, and to describe a few typical motors as illustrations of the principles involved and their application.

Demand for Small Machines.—Perhaps the most striking fact which appears on a first survey of the field is that small machines are much more frequently required as motors than as generators. With the development of large power stations for the production of electrical power in bulk, and for its sale to consumers in either small or large quantities, the necessity for small users of electrical power to generate their own current very seldom arises. On the other hand, the very extension of the means by which electric power can be obtained easily and cheaply from mains brought to the consumers' doors has enormously increased the demand for small- and moderate-sized motors, until the design and manufacture of such machines has become a special industry and has led to the evolution of

many patterns which bear little resemblance to the large generators which attract so much attention.

Even in places where large amounts of power are required—as, for instance, in large factories—it is frequently convenient to subdivide the power into small units, and to apportion a separate motor to each machine or group of machines, thus saving the expense of costly and wasteful shafting, rather than to drive the whole factory from one large motor, as is usually both necessary and economical where the power is obtained directly from steam plant. Perhaps the greatest advantage of an electric motor in industrial work is the ease with which the electric power can be conveyed to it, thus enabling it to be installed at the nearest point to the machine it has to drive, and in some cases even to be incorporated with and made part of the machine.

Conditions of Working:—But this very advantage increases considerably the onerousness of the conditions which the motor may have to face. For instance, it may be set to work on the ceiling or walls of a dirty and dusty room in a factory where some not very cleanly trade is being carried on; or it may be placed in the workings of a coal mine amidst very trying surroundings; and in innumerable other positions its mechanical and electrical properties may be exposed to much more severe strains than a generator is called upon to face. What, for instance, could be worse than the position of a tramcar motor underneath the vehicle on a wet and wintry day? In this and many other cases it is absolutely necessary that the whole of the working parts of the motor shall be protected from external influences, such as water, dust, explosive gases, etc. This necessitates the designing of *enclosed motors*, which in some cases have to be packed into a small space, and these conditions have reacted upon the design until machines have been produced (see Fig. 630) which bear little external resemblance to any known generators. Then, again, the conditions of speed and changes of speed and load are also in many cases much more trying than the corresponding conditions in generator working.

It follows from the above that in designing a motor attention must be paid to the conditions under which it may have to work, and very careful consideration must be given to many small details which may be either neglected or relegated to a comparatively unimportant place in the design of a generator. There is, indeed, one frequent requirement of a motor, peculiar to it and distinct from any similar requirement in a dynamo, and that is that it should have a *large starting torque* without using an excessive amount of current. This feature is necessary whenever the motor has to start with either the full, or a considerable fraction of the full, load on, as when it is geared up to a machine set so as to absorb most of the rated power of the motor. A motor which is defective in this respect must be started with a light load only, and this may necessitate additional clutches or

other devices for throwing on the load after the motor has got under way.

Classification:—It is this great variety of conditions under which electric motors have to be used which renders the question of standardisation—to which allusion has been made on page 202—such a difficult one for manufacturers. It also renders the question of classification difficult, as so many cross-classifications are possible. The following, which deals with the motors from the user's point of view, will perhaps be a convenient classification to adopt:—

- | | | |
|-----|--------------------------|--------------------|
| (a) | High and moderate speed— | Open-type motors. |
| (b) | " " " | —Enclosed motors. |
| (c) | Slow speed | —Open-type motors. |
| (d) | " " | —Enclosed motors. |
| (e) | " " | —Traction motors. |

In this classification the question of voltage is ignored, and even the terms adopted—such as open and enclosed, high, moderate, and low speed—are open to criticism, for there are motors built which, although not completely enclosed, are nearly so, and, as a matter of fact, the question of whether a motor shall be quite open, or be made quite gas tight, chiefly affects the outer casing, and has, in many machines, little effect upon the details of the electric and magnetic circuits. Such details, as well as the general form of the motor, are more affected by its conditions of work.

Similarly, the speed division is vague and relative, and different manufacturers place the lines of division differently. Thus, one firm classes as "low speed" machines running up to a speed of 1,200 R. P. M., and as "moderate speed" machines running at 1,030 R. P. M. These speeds appear to be certainly too high for the more commonly accepted meanings of the terms. Another firm does not describe as low speed motors any machines running at over 400 R. P. M. This seems more reasonable. On a review of the whole case we propose to fix the limit between low and high speed at 500 R. P. M.; and although up to 1,000 R. P. M. the motors may be called "moderate" in speed, such an additional classification does not offer any advantage here. In the early days only machines which would now be put in the high-speed class were available; but with the better knowledge of electrical and magnetic laws as the science developed, designers have been able more and more completely to satisfy the ever-widening demands of the users, until it may fairly be said that at the present time electric motors can be obtained to run at speeds varying from almost dead slow to 3,000 or 4,000 R. P. M.

As other bases of cross-classification may be mentioned the number of poles—i.e. the machines may be bipolar or multipolar; the excitation of the fields—series, shunt, differential or compound; whilst motors for trac-

tion purposes form a class by themselves. The description of a few representative machines will illustrate in due course the various differences referred to.

Since, as already remarked, the chief principles of construction of continuous current machines, whether generators or motors, have been dealt with in detail in Chapter I. (*see* page 7 *et seq.*), it is not proposed in this chapter to take up separately the various parts, such as "the field magnet," "the magnetic circuit," "the armature," etc. Instead, it will be more convenient, to adopt in a general way the speed classification given on page 577, and to point out, as they arise, the instances in which the general principles have been applied in any special manner to meet the varied requirements met with in practice.

I.—MODERATE- OR HIGH-SPEED MOTORS

Motors of this class when of the open type, are the ones which most nearly resemble the generators already described; they depart most from generator types when they are partially or almost wholly enclosed. We may therefore first briefly consider machines which have been designed to be used either as dynamos or motors according to circumstances, and it will at this point be convenient to notice some of the chief theoretical and other differences between the same machines when run as dynamos and as motors.

Interchangeable Dynamos and Motors.—As already explained, in Volume I. the electric generator is a reversible machine, and any good generator may be run as a motor. It must, however, be noted that the power in a motor is travelling in the reverse direction, and that the conductors and core plates are driving the shaft instead of the shaft driving the core plates and the conductors. Where, however, the conditions of work permit, any well-designed generator may be run as a motor, and most modern motor manufacturers in designing their standard machines of the open or partially enclosed type—especially the smaller ones—keep the generator requirements in view, so that they may be used in either capacity under ordinary conditions of running.

Dealing first with *shunt-wound machines*, it should be noted that the terminal P. D. cannot well be the same in the two cases if the machines are identical. The equations already given for this terminal P. D. (V) are

$$\begin{aligned} V_1 &= E - C_a r_a \quad \dots \quad \dots \quad \text{for a dynamo,} \\ V_2 &= E + C_a r_a \quad \dots \quad \dots \quad \text{for a motor,} \end{aligned}$$

where E is the generated E. M. F. and C_a and r_a are the armature current and resistance respectively. Now with identical machines running at the same speed and the same terminal P. D., the fields and therefore the E. M. F. would be the same, which is impossible according to the above equations,

for in one case E is greater and in the other less than v , and, therefore, with the same value of E , v_2 must be greater than v_1 . But this will give a larger field flux, with which the machine must be run more slowly to keep the value of E the same. In practice, also, where the same types of

machine are required to act both as generators and motors, it is absolutely necessary, because of the loss of voltage in the distributing conductors, that the rated P. D. of the generators should be higher than that of the motors. With the diminished P. D. the field flux in the motor is diminished, but the back E. M. F. required is also much more diminished, because the flux does not diminish proportionately with the P. D., and therefore on the whole the speed of motors, as well as their voltage rating, is less than that of identically constructed generators.

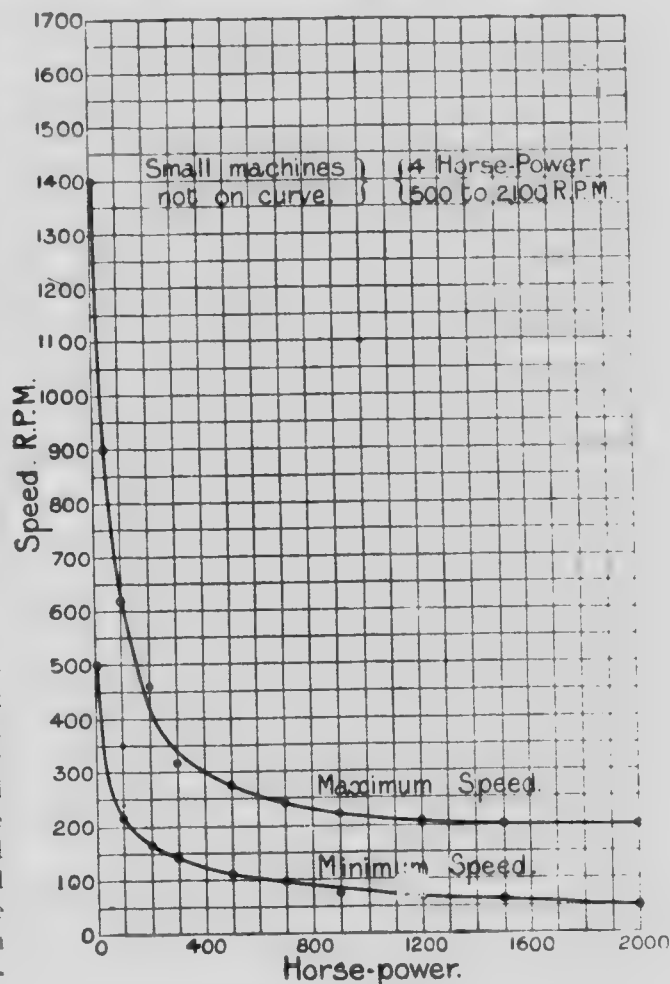


Fig. 572.—Relation of Power to Speed in Ordinary Electric Motors.

For example, instances can be found of standard dynamos rated at 120, 240, and 500 volts, whereas the same machines as motors are rated at 115, 230, and 480 volts respectively. In regard to speed, a 40-kilowatt machine of this pattern, which is to be run at 725 R. P. M. as a dynamo,

runs at 625 R. P. M. as a motor. These instances will suffice to illustrate the point mentioned.

The use of *series-wound machines* as generators is not common, while their use as motors, especially in traction work, is extensive, and will require to be specially dealt with. It is unnecessary therefore to enter here into a comparison similar to the above. Also machines *compound wound* for regulating purposes present, as motors, problems different from those which they present as generators; these problems will be referred to when dealing with regulation.

Output and Speed.—Before proceeding to consider further details of modern continuous current motors, it will be of interest to notice the connection between speed and output in such ordinary motors as we are now considering, in which the designers have not been called upon to face abnormal requirements in the conditions, or for either slow or very high speeds. Such a connection is given graphically in the curves of Fig. 572, in which the horizontal distances represent horse-power and the vertical distances speed in revolutions per minute. These curves have been obtained from an examination of the speeds and outputs of a very large number of motors in actual use, and may be said to apply to ordinary standard machines. Two curves are drawn; that marked "maximum speed" gives the upper limit usually obtaining, whilst that marked "minimum speed" indicates the ordinary lower limit. Small machines built specially for "slow" speeds are excluded, for, as we shall see later, it is possible to construct motors of small output to run at 100 R. P. M. or even less, but such machines are heavy and costly relatively to the work they can do. It will be noticed that, as might be expected, the ordinary speeds depend to a great extent upon the output demanded, and that as the latter increases the permissible speed diminishes, but that the rate of diminution is not great for machines over 700 H. P. Another point worth noticing is that the range, as shown by the ratio of the maximum to the minimum speed, is fairly wide; thus, for large machines of 2,000 H. P. the speeds lie between 200 and 50 R. P. M., and at 400 H. P. between 300 and 125 R. P. M. The high ratio extends, however, to all sizes, for as low as 4 H. P. the speed ranges from 2,100 to 500, a ratio of more than 4 to 1.

Rating.—Closely connected with the above is the question of the rating of electric motors, a full discussion of which would carry us beyond the limits of the present work. It may, however, be explained that the usual method is to refer to the different machines as capable of giving so much mechanical power, which, as it can be absorbed in friction on an appropriate brake, is, as a rule, specified as so many **Brake Horse Power (B. H. P.)**. But, as already pointed out (see page 603, Vol. I.), the mechanical power delivered depends upon two things—namely, turning moment (or torque) and speed. For the same turning moment developed

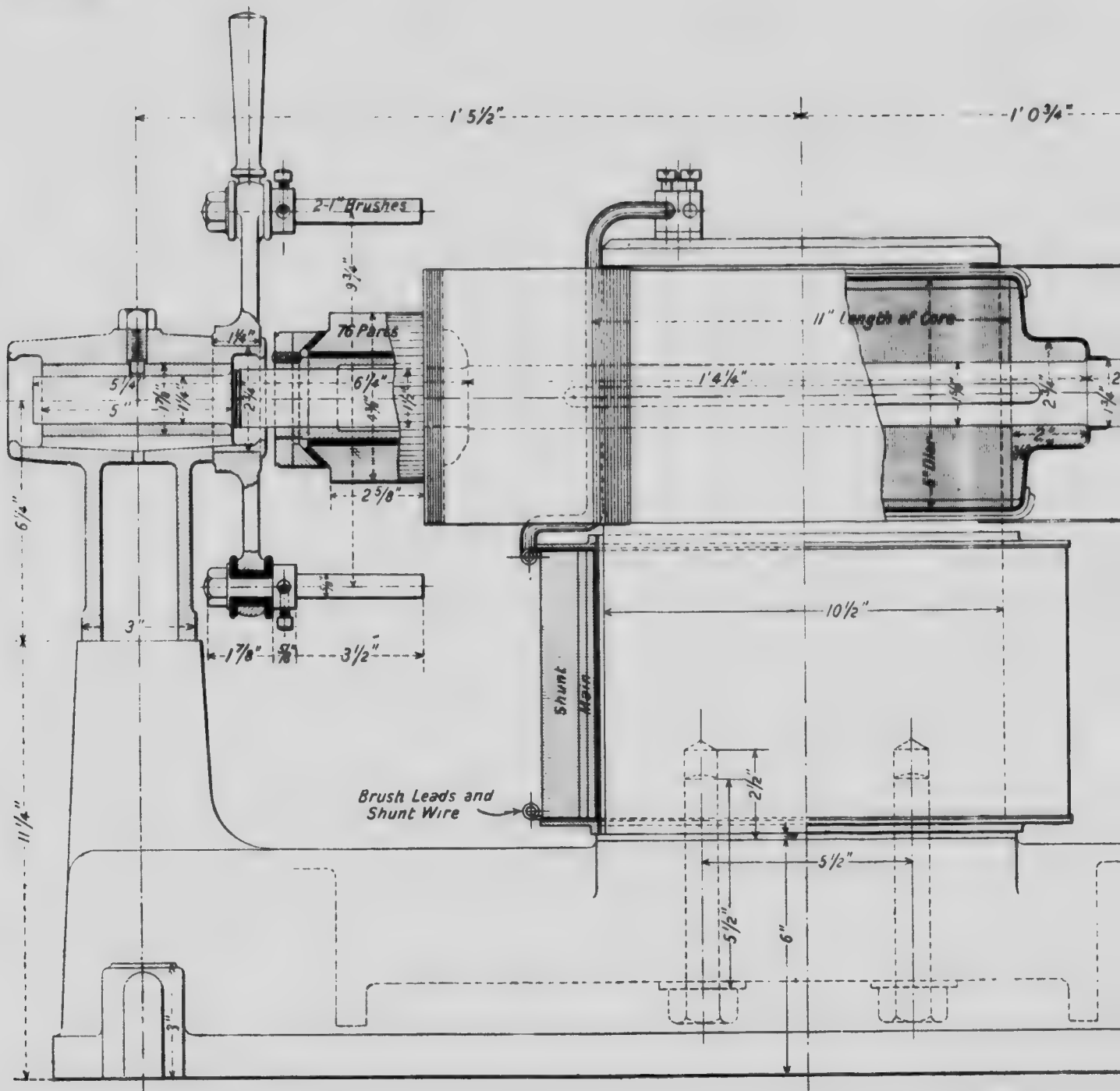
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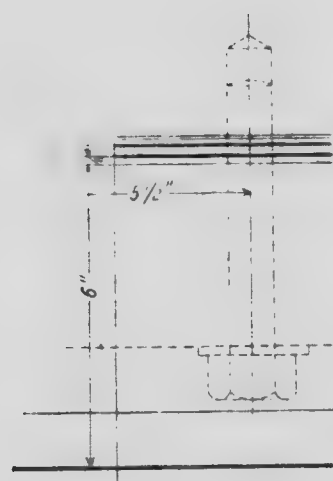
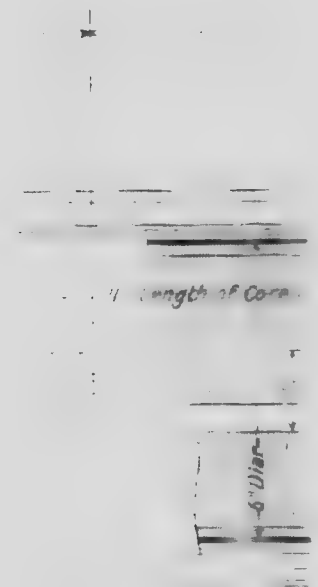
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PLATE IX





by the structure, the power can be made to vary through wide limits by varying the speed, as well as B.H.P. therefore, should be specified in the rating, as on the Crocker-Whitcomb slow-speed motors, which will run at 150 R.P.M. or 100 R.P.M., which is the standard speed adopted.

It should be noted that a motor rated to give 75 H.P. at 150 R.P.M., or 100 R.P.M., will, at 100 R.P.M., with certain allowances, be able to give 100 H.P. for electric motors, however, is complete, unless the temperature at full load on a long run is clearly specified. The first object of over-running the machine is to increase the steady temperature which it attains if the load be kept on for a sufficient time. Most well-built motors will easily stand a fair percentage of over-load for short periods of time if only the electric energy be supplied in the proper form, and, indeed, this is one of the advantages of this form of power. But the steady temperature reached in a long run must not be allowed to become excessive. For open-type motors under the full rated load, the temperature should not exceed 40° or, at the most, 45° Centigrade in any part of the commutator, which may be allowed to get a little warmer. The temperature limits for enclosed motors will be referred to in due course.

Actual Machines.—As an example of a high-speed machine built, specially to work as a motor, but which may also be run as a generator, we give in Plate IX., a fully dimensioned drawing of a 6 B.H.P. motor, constructed some years ago, by Messrs. Johnson and Phillips, and used for driving in the electrical engineering laboratory at the Northampton Polytechnic Institute. The machine is designed to give the above power when running at 1,420 R.P.M. on 100-volt continuous current mains. The drawing gives the various details so fully that very little further description is called for, especially after the very full manner in which the design of continuous current dynamos has been discussed. We may, however, point out that the machine is a smooth-core drum-wound machine, with four fibre or wooden driving horns at 90° apart. The non-magnetic gap from iron to iron is $\frac{1}{8}$ inch, and when the copper conductors are packed into this space in two layers, the mechanical clearance is very small. On the field-magnet limbs the series winding is placed next to the core beneath the shunt windings.

As another example of a well-designed, though not very recent, machine, Plate X. is a detailed drawing of a 2 B.H.P. slotted-core motor, built by Messrs. Crompton and Co., and used for driving the wood-working shop at the Northampton Polytechnic Institute. This drawing, like the last, gives so much detail that very little description is needed. In regard to the magnetic circuit, attention may be called to the fact that the magnet cores are continued to beyond the top of the armature, which they are partially hollowed out to receive. They do not, however, provide the whole

of the pole face, for polar horns, embracing a considerable part of the armature, are keyed on to them. To promote sparkless running the curvature of these horns is less than that of the rest of the pole face, so that the gap widens towards the pole tips. The horns are of cast iron, to still further diminish the permeance. The armature core is slotted with nearly closed slots, of which an enlarged drawing is given. In each of the slots there are shown two stranded conductors, which are almost imbedded in the iron by the projecting faces of the teeth. The strands are, of course, twisted in the usual manner to kill the eddy currents in the copper. It will be noticed that, as is also the case in the Johnson and Phillips motor (Plate IX.), the armature core extends down

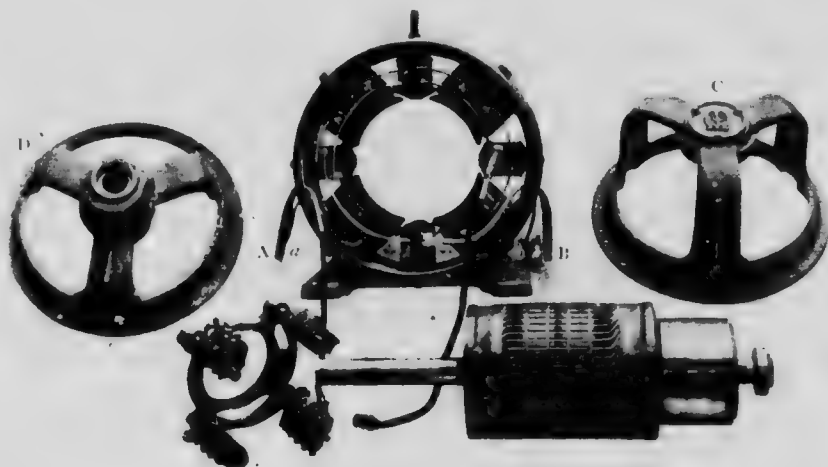


FIG. 573.—Details of Mather & Platt's "P"-Type Motors.

to the shaft of the motor on which the core plates are threaded and keyed. This practice is very usual in small motors because of its mechanical advantages and its convenience as compared with spider-driven core discs. It, however, renders efficient ventilation of the core impossible, and therefore raises the maximum working temperature at full load. The discs are further held in their places by end plates screwed on to the shaft and locked in position by a pinching screw. The "Half Section on E. F." shows the details of the pedestal to which the bearing containing the oil chamber and the lubricating rings is bolted.

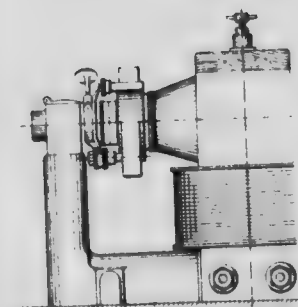
Both the above machines have been some years in use, and therefore represent a somewhat old type, but they were built in accordance with sound modern principles, and a careful study of the details given in the drawings will be advantageous.

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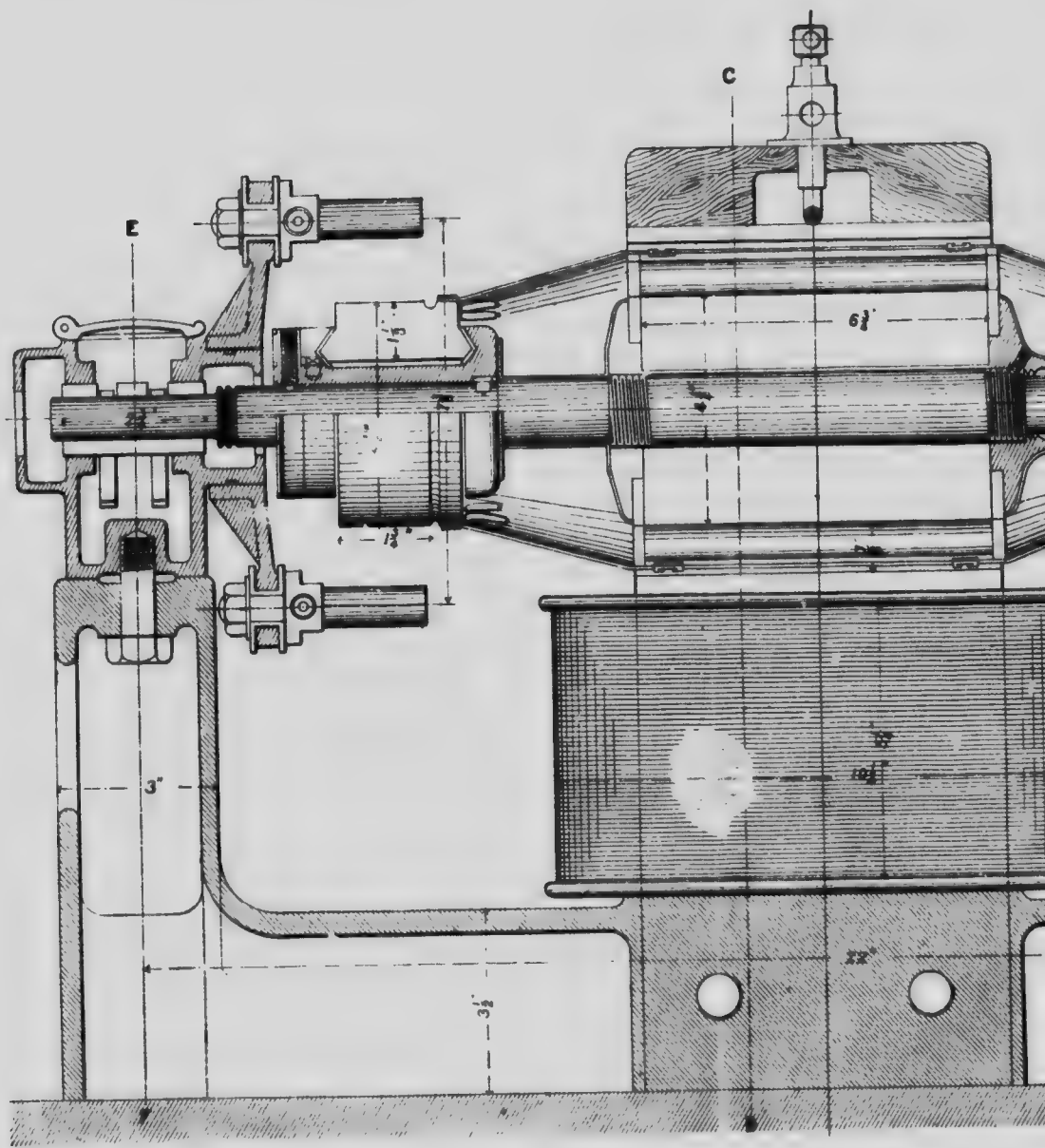
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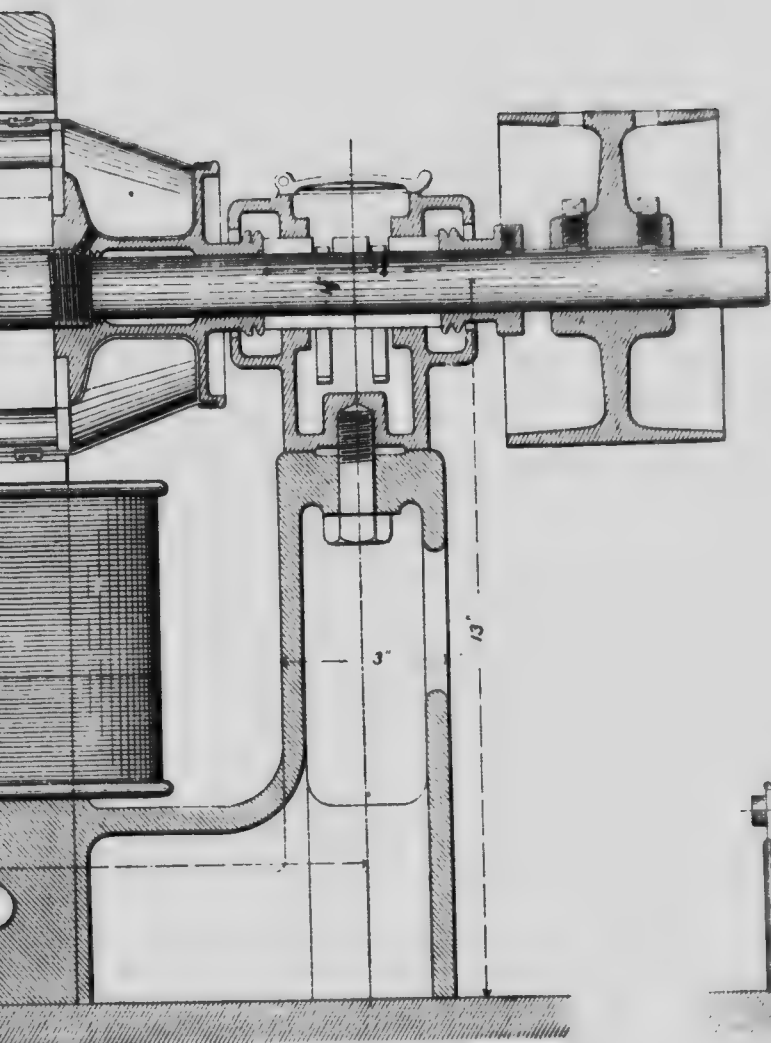


SIDE ELEVATION

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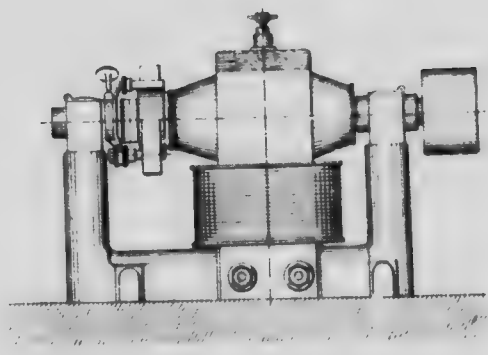
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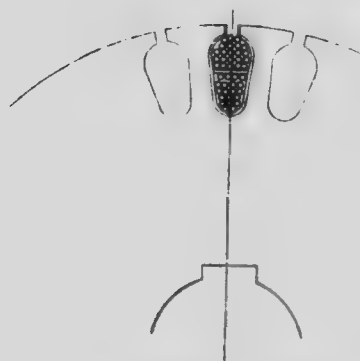
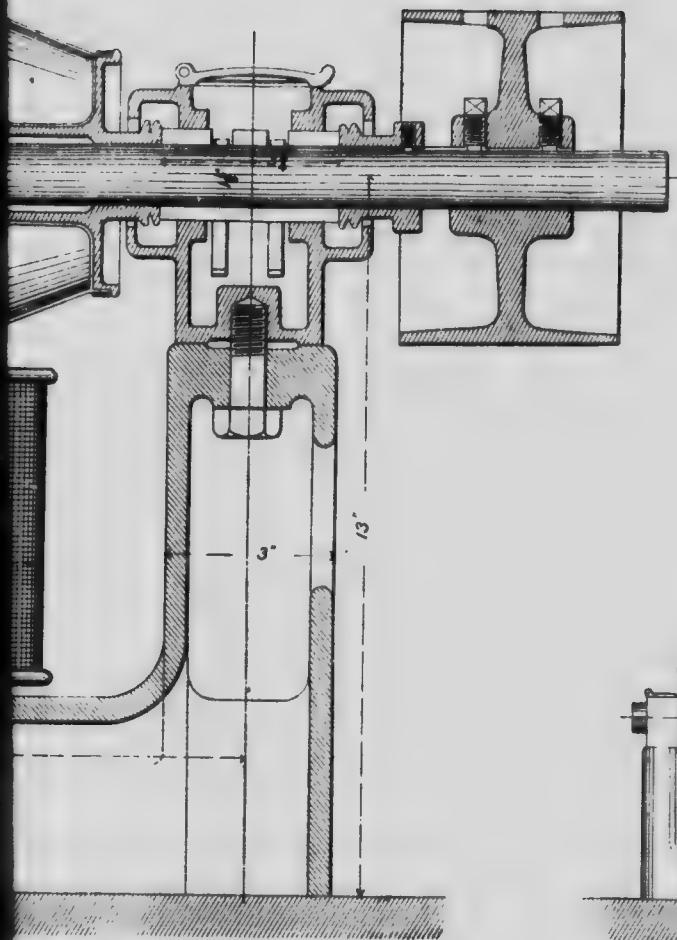


DETAIL OF SLOTS

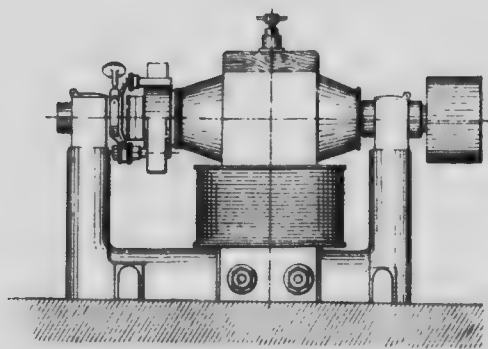


SIDE ELEVATION

CROMPTON CONTINUOUS CURRENT MOTOR, 2 H. P. AT 1,100 R. P. M.



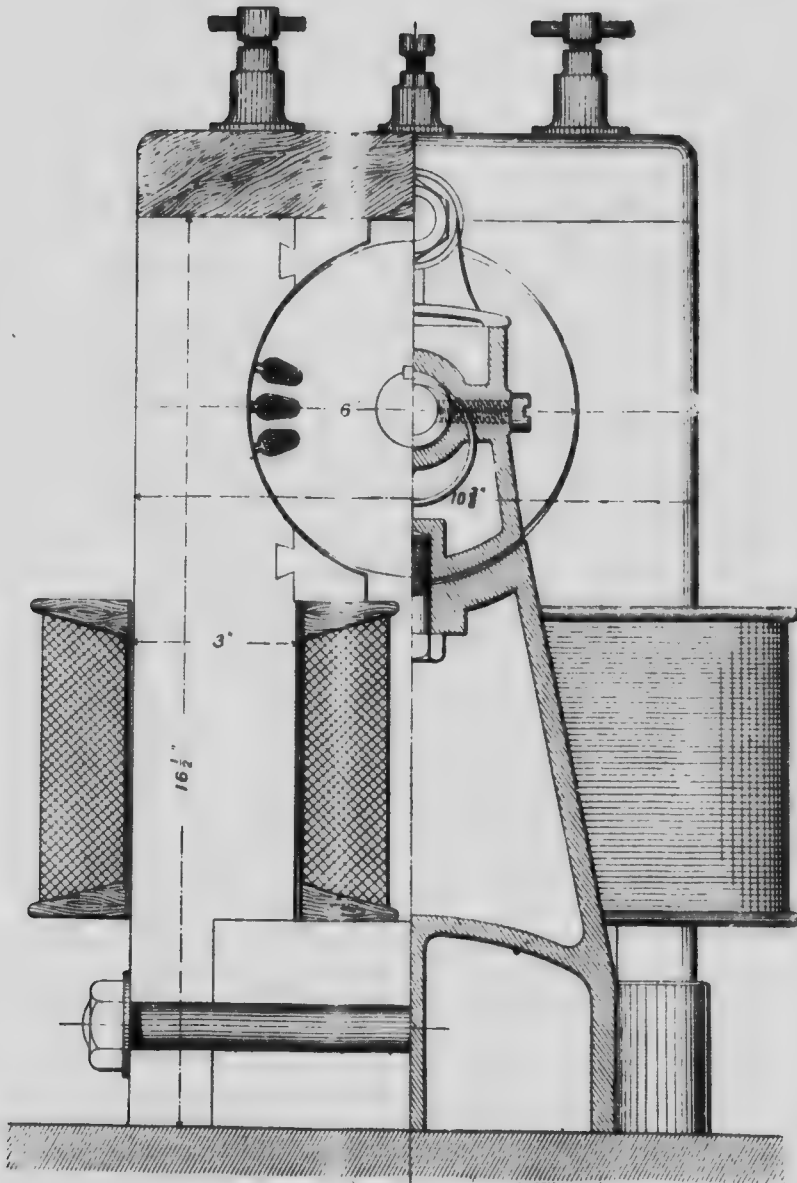
DETAIL OF SLOTS



SIDE ELEVATION

CROMPTON CONTINUOUS CURRENT MOTOR, 2 H. P. AT 1,100 R. P. M.

PLATE X



HALF SECTION
ON C.D.

HALF SECTION
ON E.F.



Modern Machines with Interpoles.—For similar reasons to those which obtain in dynamo design, namely, to assist the commutation, especially when the conditions are not advantageous, interpoles have been introduced into the design of many types of continuous current motors. It is not necessary to recapitulate here the arguments which have been already given (*see pages 107 et seq.*) for their use, and which, to a great extent, apply unchanged to motors, the differences on the effect of armature reaction, which are dealt with elsewhere, being, of course, kept in view. Leaving over for the present the cases in which interpoles are not used, a few examples will first be given in which they are employed.

As a good example of a modern continuous current motor of the open or unenclosed type and using interpoles, Fig. 573 shows the details of one of the standard motors built by Messrs. Mather and Platt, and Fig. 574 gives a view of a complete machine. It will be noticed that the yoke ring is of simple design; it is made of cast steel of high permeability, and has ample cross-section for the magnetic flux. The feet upon which the motor stands are cast in one piece with the ring. The end covers, which are shown separately in Fig. 573, are of cast iron. The magnet cores are laminated, and are bolted on to the yoke ring, the pole shoes being continuous with the cores. There are four main poles which are excited by a shunt current from leads *a* and *b*, which are brought out through two bushed openings, one on either side of the ring, and close to the main leads, A and B. This enables a regulating resistance to be placed in the exciting circuit. There are also four interpoles which fulfil similar functions to those for which they are used in generators, in connection with which they have been fully explained already (*loc. cit.*): It may, however, be remarked that such poles are more useful in motors than in generators, because of the more severe conditions of working which have been already alluded to. The interpoles are excited by the current which passes through the armature. The terminals of the exciting circuit can be seen in Fig. 573, and it will be noticed that one of the main leads B

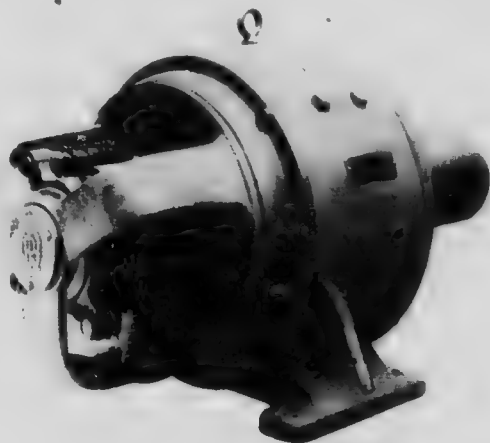


Fig. 574.—Mather & Platt "P"-Type C. C. Motor.

is directly connected to one of these terminals, the other terminal being provided with a flexible lead for direct connection to one of the brush terminals. The other main lead A goes direct to the brushes.

The armature is of the slotted type with one ventilating duct. It is similar to some of the dynamo armatures already described in detail, and is very substantially built. The coils are "former" wound, and are finished to fit the machined slots exactly, and to fill them without the slightest pressure; the usual processes to ensure absolute freedom from moisture are employed in their construction.

The brush gear is carried upon a collar which is clamped upon a hub cast on the commutator end cover C.



Fig. 575.—Carcass of a Siemens Standard Motor.

There is no arrangement for rocking the brushes, as owing to the use of interpoles, the brushes can be fixed once for all in the symmetrical position which enables the motor to be run in either direction. The brushes are of carbon in the special form of brush holder designed by the makers, some of the details of which can be made out in Fig. 573; it is of the box type, with flexible conductors across the loose joints.

At the commutator end the shaft runs in ball bearings, which are grease-lubricated, thus avoiding the trouble which arises in some patterns of motors through the lubricating oil leaking through to the commutator. At the pulley end

the cover D is designed for oil-ring lubrication of the bearing, but the oil-channels provided ensure that there shall be no oil-flinging or creeping towards the armature, even at the highest speeds.

The particular motor illustrated in Fig. 574 is one only of a standard line of motors, of which twelve different sizes are built with outputs ranging from 1.5 to 105 B. H. P. and normal speeds from 240 to 1,600 R. P. M. The windings are for one of four standard voltages, namely, 110, 220, 440, and 500 volts. The limit of temperature rise is 75° Fahrenheit (42° Centigrade) after a run of six hours at full load, but the motors will stand a 25 per cent. overload for two hours, and will run momentarily with 100 per cent. overload without sparking.

The above motor has been described very fully as a typical motor, which has many features in common with all good motors of modern design.

In subsequent descriptions it will not, therefore, be necessary to refer to all these features with the same detail.

For comparison, both as to points of resemblance and points of difference, Fig. 575 shows the carcass of a four-pole standard motor, as built by Messrs. Siemens Bros. Dynamo Works, Ltd. Here again the laminated cores and pole shoes are continuous, and are bolted to the magnet frame. Interpoles also are used to secure good commutation with fixed brushes, but they are not usually supplied with machines of a less output than 15 B. H. P. at 900 R. P. M. The standard sizes range from 0.25 B. H. P. at 700 R. P. M. to 150 B. H. P. at 780 R. P. M., the normal speeds varying from 340 R. P. M. to 2,700 R. P. M.

As a further example of a modern interpole motor, one of the standard interpole motors of the Lancashire Dynamo and Motor Company, Ltd., is shown dismantled in Fig. 576. These motors are built in twelve different standard sizes, and are specially designed for each motor to have a very wide range of speed; in fact, they belong to the class of motors which may be fairly described as "variable-speed" machines. For this purpose interpoles are introduced into



Fig. 576.—The Lancashire Dynamo and Motor Company's Interpole Motor.

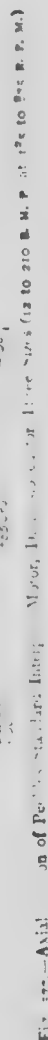
the smallest size, in which the power handled may be as low as 0.5 B. H. P. with a speed variation of from 200 to 800 R. P. M., or as high as 4 B. H. P. with a speed variation of from 1,530 to 2,200 R. P. M. In the largest standard size the power may vary from 16 B. H. P. at 110 to 4.0 R. P. M. to 80 H. P. at 524 to 1,100 R. P. M. Similar machines with six poles are built up to 140 B. H. P.

The magnet yoke is of cast steel with solid cores projecting inwards, but with laminated pole pieces, the shape of which can be readily made out in the figure. In the six largest sizes the magnet frame is split along the horizontal diameter as shown, but in the smaller sizes it is continuous. Swivel bearings are used carried as shown in the figure; they are of the self-oiling type, with oil rings and oil wells, the latter being provided with overflows to prevent over-filling. The armature is substantially built, and is of the cylindric-barrel type; it is well ventilated and provided with a large commutator. The commutator bearing is carried by a two-armed bracket projecting from a circular ring attached to the magnet yoke by four bolts equally spaced, so that in whatever position the motor has to be fixed, the oil well may be upright. Details of the brush gear and the exciting coils will be given later.

It has been remarked more than once above that the standard machines described are built in many different sizes for a very wide range of powers and speeds. It is shown elsewhere (*see* Section VI., page 641 *et seq.*) that the speed depends upon the supply voltage, the windings, and the field excitation, as well as upon the load. Hence carcasses of a particular size can be wound so as to give machines capable of running at different speeds under different loads when supplied with energy at various voltages. On the other hand as the size of the carcase is changed without changing the type, the above ranges of conditions under which it becomes available necessarily change, though the machines of one size may overlap those of another. It will, therefore, be interesting to consider one or two examples of standard motors in connection with the actual dimensions of some of the different sizes.

For this purpose there is given in Fig. 577 a section of the carcase of an enclosed interpole motor, as constructed by Messrs. Bruce Peebles and Co. The principal dimensions are inserted on the drawing for three different sizes of the machine, known as the C 10, C 12, and C 14 sizes respectively. Of these sizes, C 10 can give from 12 to 60 B. H. P. at speeds varying from 185 to 800 R. P. M.; size C 12 can give from 25 to 130 B. H. P. at speeds varying from 225 to 875 R. P. M., and C 14 can give from 47 to 210 B. H. P. at speeds varying from 230 to 760 R. P. M. All the dimensions are given in millimetres (25.4 mm. = 1 in.). The outside appearance of the motors is shown in Fig. 578, in which some additional dimensions of the different sizes are given. The machines being built by the same manufacturers as

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To form the cover, extensions are fitted on to the casting, which con-

stitutes the yoke ring, reaching as far as the middle of the bearings, and completely covering the commutator in a coned case, in which there are large openings, which can, however, be covered with perforated or continuous covers, as may be required. These extensions also carry the bearings, for which there are no separate pedestals. The openings can be more or less completely closed, but these motors are not intended to be hermetically sealed, but only, when most closed, ordinarily dust-proof. When most open the excess temperature at full load does not exceed 70° F. (39° C.).

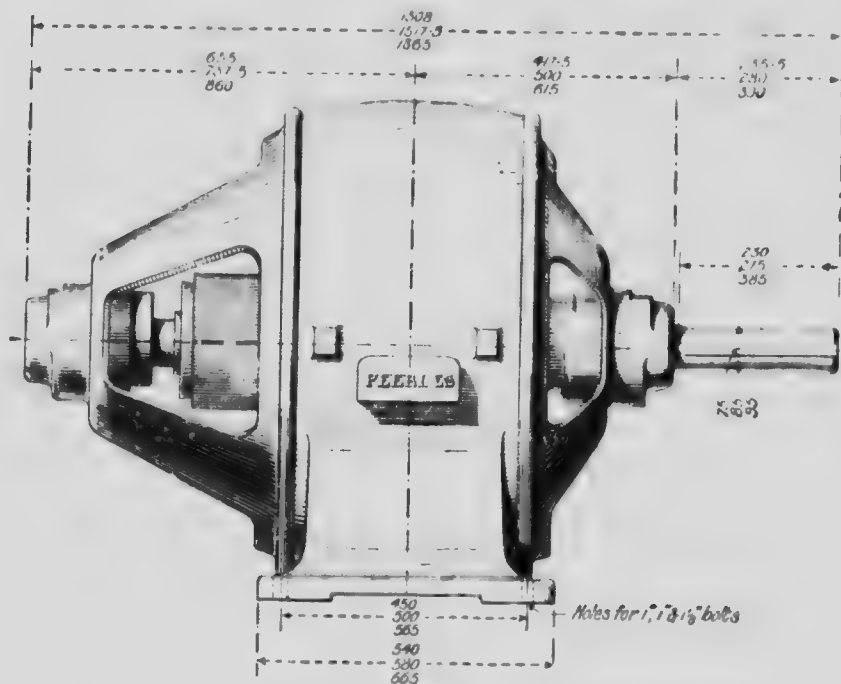


Fig. 578.—Outside View Dimensioned for Three Sizes of Peebles Standard Interpole Motor.

but when fully enclosed this excess temperature rises to 90° F. (50° C.) above the temperature of the surroundings.

For the largest size the armature core is 310 mm. (12.2 inches) long, and there are four ventilating ducts running through the core plates, which extend nearly down to the shaft. The outside diameter of the core discs varies from 313 to 515 mm. (11.9 to 20.2 inches) for the different sizes, the number of discs used, and therefore the axial length, being also increased as the size increases. The over-all length, with a liberal allowance of shaft for the pulley, varies from 1,308 to 1,865 mm. (51.5 to 73.5 inches). It should be noticed that the faces of the magnet poles are laminated, and

Architectural floor plan of a circular building, likely a church or cathedral. The plan shows the interior layout, including the nave, choir, and various chapels. The building is oriented with a compass rose indicating North (N) and South (S). Dimensions are provided along the top and left edges.

Top dimensions: 9001, 456, 699

Left dimensions: 612, 620, 961

Figure 1
Brush Station 1, 14 H₂O" Meter, Dimensioned for Three Pipes, to be Packed with the Bunk

mutator end, and in the lower part on the right-hand side a view with the bracket and brush gear removed. The upper part on this side is a section through the magnetic circuit showing the yoke, core and pole face of the magnet, and the slotted iron of the armature.

Fig. 580 shows two longitudinal sections through the axis of the machine. The upper half section passes through the centre of one of the main magnet cores, and the lower half section passes through the middle of one of the interpoles. Both sections give details of the armature and its ventilation, of the commutator and the brush rocker, and of the ball bearings, the races for the balls being clearly depicted.

The yoke of these motors is of cast steel and the pole cores and faces of high permeability stampings of the shape shown. The relative sizes of the main poles and interpoles can be made out approximately from the drawings, and it will be noticed that the latter, besides being very narrow (24 mm.) parallel to the gap, are axially much shorter than the main poles, being only 75 mm. as against 136 for the main poles.

To avoid confusion in the dimensions, which are all in millimetres, triple sizes are only given for the chief



Fig. 581.—Brush "H.O." Motor.

dimensions and the single dimensions have reference to the smallest of the sizes dealt with in the triple numbers. This smallest size (H.O. 9) is rated to give from 5 to 15 B. H. P., at speeds varying from 420 to 500 R. P. M. The next or intermediate size (H.O. 15) gives from 17.5 to 40 B. H. P., at 400 to 760 R. P. M., whilst the largest (H.O. 40), which is the largest of the standard sizes, gives from 45 to 100 B. H. P. at 350 to 670 R. P. M. These motors are wound for two standard voltages, namely, 250 and 460 volts. It is claimed for the ball bearings that they reduce the friction losses to a minimum, and thus materially increase the efficiency of the motor, more especially on light loads, and that they also substantially shorten the length of the shaft, and thus enable a more compact machine to be built, a point not without importance where space is limited. The external appearance of the open (protected) type (H.O.) is shown in Fig. 581:

Modern Machines without Interpoles.—A little consideration will

show that the addition of interpoles in the motors described above must, in any case, add to the cost of a machine of a given size of carcass, although there are counterbalancing advantages which may be worth paying for in this way. In large machines the increase of cost is not a serious matter when compared with the advantages obtained, but in small machines this may not be the case, especially as the difficulties of commutation are not so serious, and quite good commutation in such machines may be obtained by careful attention to small details of design. It was remarked above, in connection with the Siemens standard motors, that interpoles "are not usually supplied with machines of a less output than 15 B. H. P. at 900 R. P. M." For sizes smaller than this the necessary results can be attained, under ordinary conditions, without using interpoles, though if the conditions are exceptionally severe, and the direction of the rotation of the motor is to be reversible, interpoles are required even in the smaller sizes.

Generally, it may be said that if a machine is required to run in either direction with fixed brushes, or to run at *widely different speeds*, or

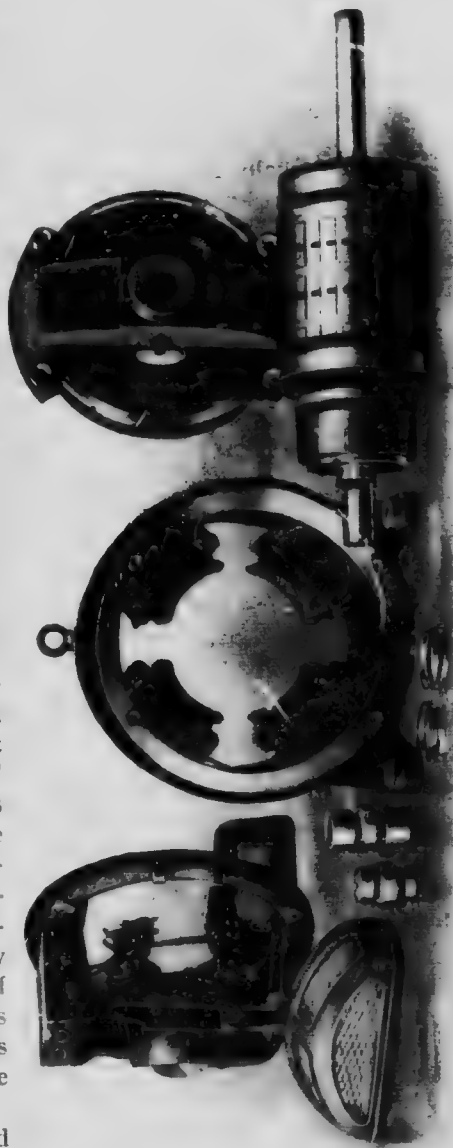


Fig. 53a.—"Lancashire" Standard Four-Pole Motor without Interpoles

to run under widely different and rapidly changing loads, it will be desirable to introduce interpoles down to much smaller sizes than would otherwise be necessary. For very small motors interpoles are found not to be worth the cost of introducing them, and a large number of standard motors, running sometimes to sizes which can scarcely be called "small" are still built without interpoles. Some of these will now be described. The larger sizes have usually four poles, but sometimes six poles, whilst the smallest have two poles only; four-pole machines will be dealt with first.

Four-Pole Motors.—From the great number of machines built it is difficult to make a selection, but as it may be useful to compare the two

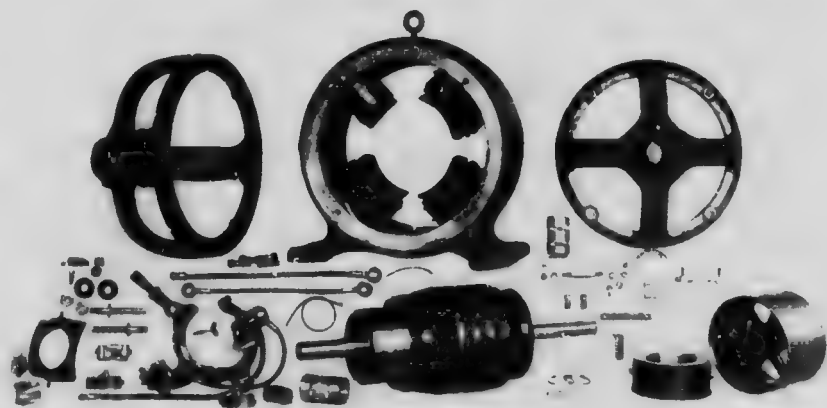


Fig. 582.—Crocker-Wheeler Standard Four-Pole Motor without Interpoles

types, Fig. 582 shows dismantled a standard four-pole motor built by the Lancashire Dynamo and Motor Company, the same firm which builds the standard interpole motor shown in Fig. 576. The machine illustrated in Fig. 582 is evidently a smaller one than that dealt with in Fig. 576. The standard sizes of the machines now under discussion are thirteen in number, the smallest size having a range of output from 0.3 B. H. P. at 200 R. P. M. to 3.5 B. H. P. at 1,870 R. P. M., and the largest size a range from 17 B. H. P. at 115 R. P. M. to 110 B. H. P. at 720 R. P. M. The actual dimensions vary from $23\frac{1}{2}$ by 22 by $20\frac{1}{2}$ inches high to $63\frac{1}{2}$ by 48 by $48\frac{1}{2}$ inches high, and the external diameter of the magnet rings from $14\frac{1}{2}$ inches to $35\frac{1}{2}$ inches; the weights vary from 300 lb. for the whole machine and 60 lb. for the armature in the smallest size, to 4,830 lb. for the whole machine and 1,230 lb. for the armature. These figures will, it is hoped, give some idea of the range covered by a single line of standard motors, and will emphasise the

difficulties of standardisation to which, in the case of dynamos, reference has been made elsewhere (see page 201).

The machines are in many respects similar to the interpole machines already described, and only one or two points need be mentioned. The bearing supports and the commutator end seen on the left of Fig. 582, and the end plate on the right are each attached to the magnet frame by four bolts so spaced that the machine may be fixed to floor, wall, or ceiling, as may be found necessary. In the six largest sizes the field frame is split across the horizontal diameter for convenience of handling, inspection and repair. Some additional details of construction will be given later.

Quite as much for points of similarity as well as for points of difference the next machine selected is of American manufacture, being a machine built by the Crocker-Wheeler Company, of New Jersey. It is shown dismantled in Fig. 583, with all its parts, even to the smallest details of bolts and washers, separately displayed. The reader will find it

useful to identify these details, and to compare them carefully, where possible, with similar details in the other machines illustrated.

In these machines cast iron is used for the frame, but the magnet cores are of steel cast-welded with the frame. These cores are of circular cross-section, and the polar extensions and the face are provided by a pole shoe which encircles the core, the end of which itself forms part of the pole face. One of these pole shoes will be seen separately at P on the extreme left-hand side of the figure. There are six standard frame sizes giving motors with outputs ranging from 3 B.H.P. at 535 to 1,070 R.P.M. to 25 B.H.P. at 700 to 1,400 R.P.M. Smaller outputs are dealt with by two-pole machines, to be described presently.

A most interesting departure in continuous current motor design has been made recently by the J.-L. Manufacturing Company, of Southall, in



Fig. 584.—Laminated Yoke-Ring of the Lundell Motor.



Fig. 585.—Laminated Cores and Pole Faces of the Lundell Motors.

connection with the Lundell motors. Earlier patterns of these motors of the multipolar type were fully described in the last edition of this book. They also had many interesting features, such as monocoil excitation and peculiarly shaped cores and pole shoes, but as they are not now manufactured, the

interest has become historical. The two-pole pattern, however, is still on the market, and will be described presently.

The new developments have reference to the improvement of the magnetic circuit by the use of high permeability sheet iron for the magnet cores and yokes instead of the cast-iron or cast mild steel which is now so largely used. It should be noted that this object of using laminated material is different from that for which it is primarily used in the armature, where its chief effect is to kill the eddy currents set up by the changing alternating magnetic fluxes. However, even in the field magnet part of the magnetic circuit lamination will facilitate the working of the motor with changing loads, especially in series- and



Fig. 586.—Field Magnets of the Lundell Motors.

compound-wound machines in which the settling down to the new conditions of a given change of excitation may be retarded by eddy currents in the cores and yokes.

Turning to details, Fig. 584 shows a built-up yoke ring of one of these modern Lundell motors. The method of clamping the laminations firmly together without piercing them with any holes can be readily made out, and the substantial character and rigidity of the whole design should be noted. The laminated core and pole face is shown in Fig. 585; the stampings for these are in one piece and are clamped together by a single bolt between massive end plates sufficiently thick to provide enough material to give a firm grip to the holding-on bolts B B, which pass through holes B in the end plates used for clamping the yoke laminations (Fig. 584). The complete field magnet is shown in Fig. 586 with the exciting coils in position, and the motor itself is shown in Fig. 587 equipped with the special brush gear and rigging, which are fully described elsewhere. The machine shown covers a floor space 23 inches wide by 27 inches long over bearings, and is 23 inches high; it has an output of 30 B. H. P. when running at 950 R. P. M. on a 440-volt circuit.



Fig. 587.—The Lundell Laminated Field C.C. Motor.

Two-Pole Motors.—For the smaller sizes of motors, as has already been stated, two-pole machines, of which there is a great variety, are extensively employed, and we illustrate in Fig. 588 a well-known and widely used pattern of this type. The machine, which is shown partly dismantled, is one of a standard line built by Messrs. J. H. Holmes and Co., of Newcastle-upon-Tyne. The magnet yoke or frame is very substantial, and is made of cast-iron, whilst the cores and pole faces, one of which is shown at A are built up of soft steel stampings of high permeability; these cores, which are of rectangular section, are bolted to the vertical sides of the frame, the magnetic flux, therefore, being horizontal. The armature coils are "former"-wound with insulated wire, taped and then placed in the grooves, in which they are held by strips of hard insulating material on the top of

the slots, and outside these by steel binding wires lying in grooves on the armature core. Steel binding wires also firmly secure the end connections. The completed armature is dried in a vacuum and impregnated with varnish after being wound. The whole armature can be removed from the machine by taking off the cap on the commutator end and removing the top bolt at the pulley end. Instructions for doing this appear on the cap referred to. The end plate, it will be noticed, rests in the frame, and is made fast by the above-named top bolt. The terminals are mounted at the top of the machine in a protective casing.

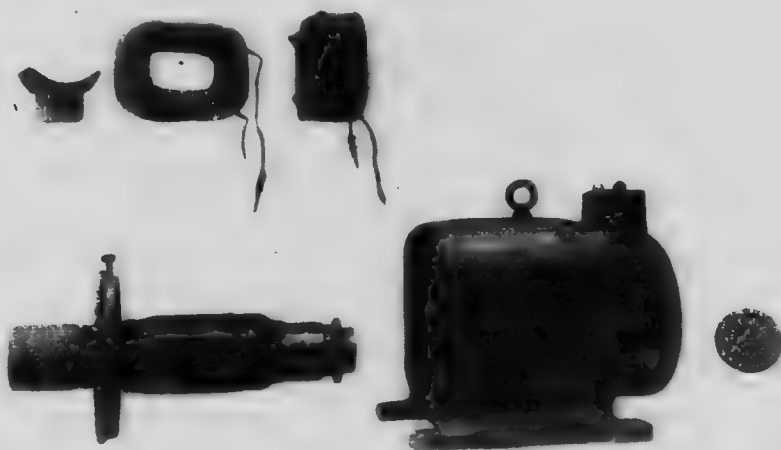


Fig. 588.—Holmes "Carter" Standard Two-Pole Motor.

There are three standard frame sizes; the smallest (4. G.) has over-all dimensions of $17\frac{1}{2}$ by $12\frac{1}{2}$ by $15\frac{1}{2}$ inches high, and outputs of about 1 B. H. P. at 1,250 R. P. M. or less or more at lower or higher speeds, and the largest (6. U.) is $23\frac{1}{2}$ by 15 by 18 inches high, with outputs varying from 2 to 3 B. H. P. at about 1,250 R. P. M.

An entirely different type of bipolar machine, the "Lundell," with non-coil excitation, has been manufactured for many years by the same firm. Messrs. J. H. Holmes and Co., and it is still one of their standard types. In many respects the machine, a sectional drawing of which is given in Fig. 589, is unique. The field magnet is excited by a single coil, but not in the same position as the coil in the Forbes dynamo (Fig. 477, Vol. I.). In the Lundell motor the axis of the exciting coil makes only a small angle

of about 15° with the shaft of the armature, and the axial flux of the solenoid is twisted, so as to pass more in the usual direction through the armature iron, which it traverses between the two poles P_1 and P_2 , shown vertically, top and bottom, in the section, and embracing about 80 per cent. of the whole circumference of the armature. The flux is thus skewed at an angle to the solenoid axis in a curious manner, and the return circuit is formed by the outer casing of the motor by two sets of paths between the regions A_1 and A_2 .

The relative positions of field magnet and armature and the exciting

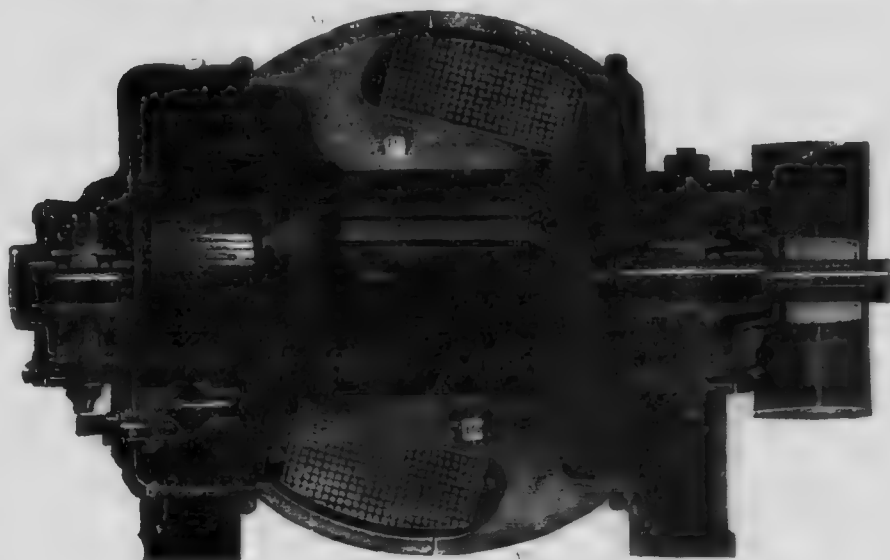


Fig. 589.—Section of Holmes "Lundell" Bipolar Motor.

coil of the field magnet are still more clearly shown in Fig. 590, in which the armature and shaft are printed in the ordinary way, and the rest of the machine—including the field magnet, brushes, bearings, etc.—are printed lightly, so as to appear in their proper positions as if they were translucent.

The armature is a drum armature, with overhanging teeth which hold the conductors in place without binding wires. The commutator is substantially built, and offers a good bearing surface to the carbon brushes used, which are held in brush holders attached to the frame without any rocking gear, so that the position of these brushes is fixed, and is the same for all loads.

The casting is in two parts, joined together in a vertical plane, each part carrying one of the pole pieces referred to above. To get at the

interior for examination or repairs the clamping bolts can be removed and the two parts separated. A reference to Fig. 589 shows that when the motor is so treated the exciting coil can be readily withdrawn and restored to its position.

As is now very common in electric motors, the lubrication is by two

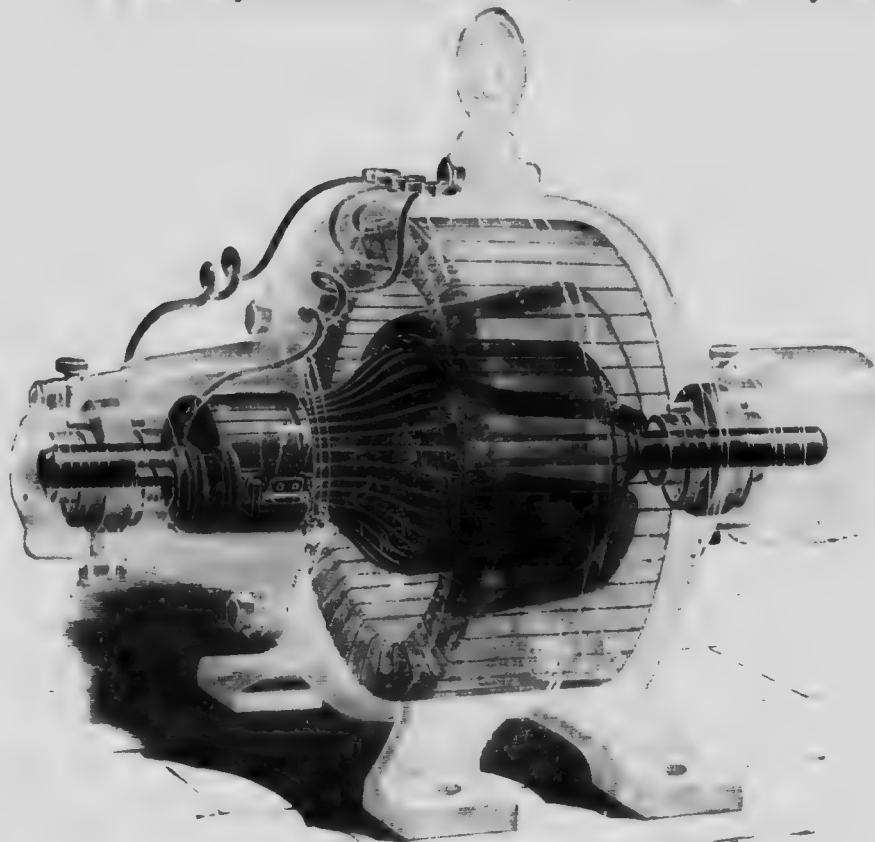


Fig. 590.—The Holmes "Lundell" Bipolar Motor.

rings moving in an oil reservoir fitted to each bearing, and therefore, the motor may be expected to run for a long period without attention on this score. Other details can easily be made out.

The motor was built in various sizes from $\frac{1}{4}$ to 10 B. H. P. and at speeds varying from 1,700 to 1,000 R. P. M. for all standard voltages from 100 to 500 volts, except that the smaller sizes up to $\frac{1}{2}$ B. H. P. were not wound for voltages above 250 volts. In the forms now used the outer carcass has been

somewhat modified from that shown in the last figure by the extension upwards of the bracket at the commutator end, so as to form a more effective protection to the brush gear and terminals, and completely enclosing the latter and the connections to the magnetising coils. This can be seen by an inspection of the sectional view in Fig. 589, but is still more clearly shown in Fig. 591, which is an external view of the present (1912) form with one of the cover doors at the commutator end open.



Fig. 591.—The Holmes "Lundell" Motor.

Small Motors.—

Electric motors of quite small powers are so serviceable and are now so widely used that their design is often specialised and differs in many mechanical details from that of larger machines. Some of the machines just described are built down to such small powers, but it will be interesting to refer to a few special designs.

The "Form L" type of continuous current motors made by the Crocker-Wheeler Company furnishes a good illustration of a series of motors



Fig. 592.—The Crocker-Wheeler Bipolar Motor Disassembled.

for small powers ranging from 0.05 to 7.5 B. H. P. at speeds varying from 440 to 1,875 R. P. M. There are nine standard sizes; the sixth in order

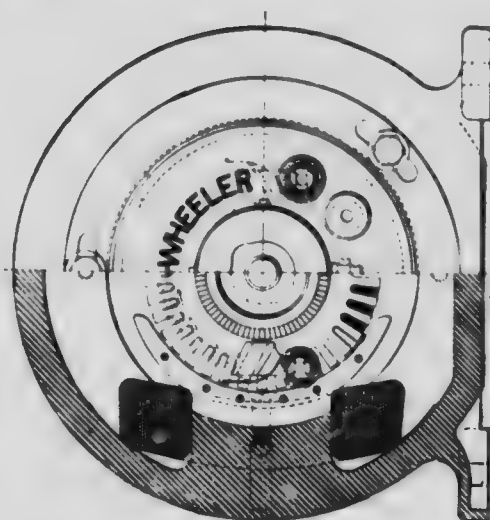


Fig. 594

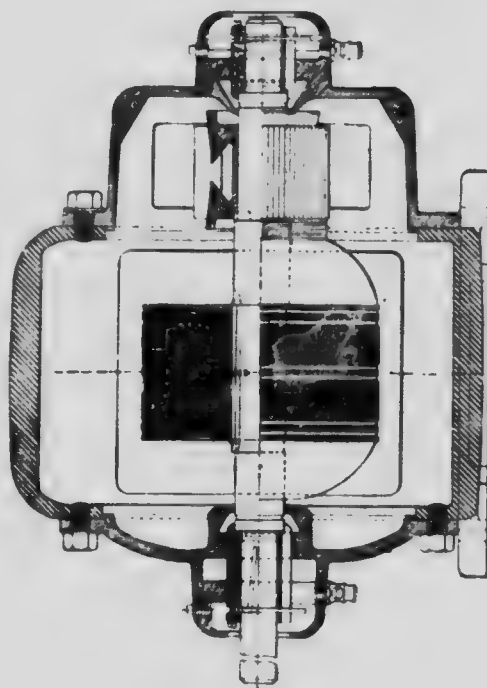


Fig. 593

Sections of the Crocker-Wheeler Small Bipolar Motor.

is shown dismantled in Fig. 592, and sectional details of the next larger size are given in Figs. 593 and 594. It will be noticed (Fig. 594) that the greater part of the magnet core is cast in one piece with the yoke frame which encloses the machine. The pole shoes are laminated, and have long horns, embracing in each case the greater part of the semi-periphery of the armature, and opening out from it towards the pole tips; the stampings are shaped to project backwards from the pole face, so as to lengthen materially the cast-iron core. Their shape can be seen at A in Fig. 592, and also in section in Fig. 593; they are attached to the core by two substantial screws with countersunk heads, and hold the magnetising coils in place. The armature is drum-wound with "former" coils, the end connections lying over one another in a manner which may be allowed in such small machines, but which has long since been discarded, for reasons previously given, in larger ones. The commutator

(Fig. 593) is simply but substantially built, and the brush gear is also simple and substantial; it will be fully described later. The frame with the magnetising coils and pole shoes in position, and with the end shields



Fig. 595.—Magnet Frame and End Shields of the Crocker-Wheeler Small Motors

removed is shown in Fig. 595, and external views of three sizes of the motor are given in Fig. 596.

The smallest size (A. L.) weighs 22 lb., is $9\frac{1}{4}$ by $5\frac{1}{2}$ by $5\frac{1}{2}$ (height) inches, with an output of 0.05 to 0.17 B. H. P. at 790 to 1,000 R. P. M., and the largest size (I. L.) weighs 376 lb., is $23\frac{1}{2}$ by $17\frac{1}{2}$ by $16\frac{1}{2}$ (height) inches, with an output of 2.0 to 6.0 B. H. P. at 440 to 1,400 R. P. M. In the two smallest sizes the laminated shoes are dispensed with and the poles are



Fig. 596.—The Crocker-Wheeler "Form L" Motors.

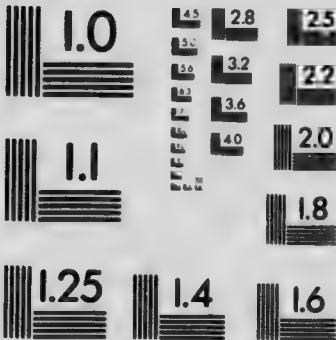
cast solid with the frame; instead, the slots are semi-closed, thus assisting the commutation.

As a final example of small bipolar motors, Fig. 597 shows, partly dismantled, a motor of this type, which is one of a standard line made by



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the British Westinghouse Electric and Manufacturing Company, Ltd. These motors are known as "Type W," and range from the smallest, having an output of $\frac{1}{12}$ B. H. P. (about 60 watts) at 900 R. P. M. and weighing 20 lb., to the largest, having an output of 1 B. H. P. at 1,200 R. P. M. and weighing 112 lb. The field poles are at the top and bottom of the frame, and the field flux is, therefore, vertical; the brushes are attached to a rocking cross-piece, A, which lies inside the vertical bracket which carries the front bearing. Other details, including the supporting rails, can be readily made out.

II.—SLOW-SPEED MOTORS

For reasons to which partial reference has already been made slow-speed motors of moderate power are very much more in demand than

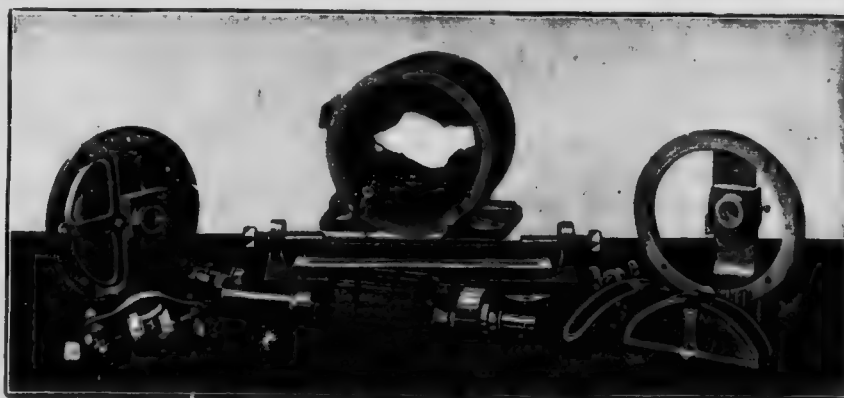


Fig. 597.—The Westinghouse Small Bipolar Motor.

dynamos of the same power and speed. In addition, it may be pointed out that there is very little to be gained by running dynamos of 1 to 10 kilowatts output at a speed sufficiently low for direct coupling to a slow-speed engine, for when dynamos of such low outputs are required it is usually easy to arrange to drive them at a high speed. With motors it is otherwise, and cases are very numerous in which a motor of less than 1 B. H. P., running at a speed of, say, 150 R. P. M., is very desirable. Many motors have therefore been designed to meet such conditions.

Generally speaking, the same result follows as in the corresponding case of dynamo machines. With the decrease of the speed the size of the machine increases, and the bipolar type is forsaken for the multipolar to secure the necessary back E. M. F. (see page 601, Vol. I.) in the armature. Moreover, for a given output the slower machine must necessarily be stronger and, therefore, more massive, because the mechanical power given (see page 603, Vol. I.) is the product of the torque and the angular velocity. Thus for the same

value of the product, if the angular velocity be diminished, the torque must be increased, and the mechanical parts of the machine must be made strong enough to stand the increased forces. All this, of course, means that a slow-speed motor is for the same power heavier and more costly than a high-speed one, but cases are not infrequent where the economies introduced—such as the saving of shafting, etc. by the lowering of the speed more than justify the extra prime cost.

With modern methods of speed control the necessity for specially designing the magnet frames for slow-speed working has diminished, the practice being to employ a frame designed to give a greater output at a higher speed. Many of the machines already described, when suitably wound, can be used for slow-speed working, but it will be interesting to examine one case of a line of motors designed specially with this object.

As a good type of such slow-speed motors, Fig. 598 is an illustration showing a type of motor built in America, and designed to give one B. H. P. at a speed of 100 R. P. M. The machine is $25\frac{1}{4}$ inches in extreme external diameter, and stands $22\frac{1}{4}$ inches high from the sole of the supporting bracket, which is $9\frac{1}{2}$ inches below the geometrical axis. The armature is 15 inches and the commutator 9 inches in diameter, and the over-all width of the machine minus the pulley is a little less than 15 inches. These dimensions are given in order that the reader may realise the actual size of the machine shown. As electric motors go it is, of course, large for the power developed, but then the speed is abnormally slow.



Fig. 598. Slow-Speed Motor, 1 H. P. at 100 R. P. M.

The motor, as is necessary for such a very slow speed, is a multipolar motor, in order that the requisite back E. M. F. may be developed. The form of field magnet adopted is shown in Fig. 599; a well-flanged yoke ring of cast-iron has cast-welded into it six cylindric wrought-iron cores, the inner ends of which form part of the pole face but are surrounded by cast-iron polar extensions, which are clamped on in the ingenious

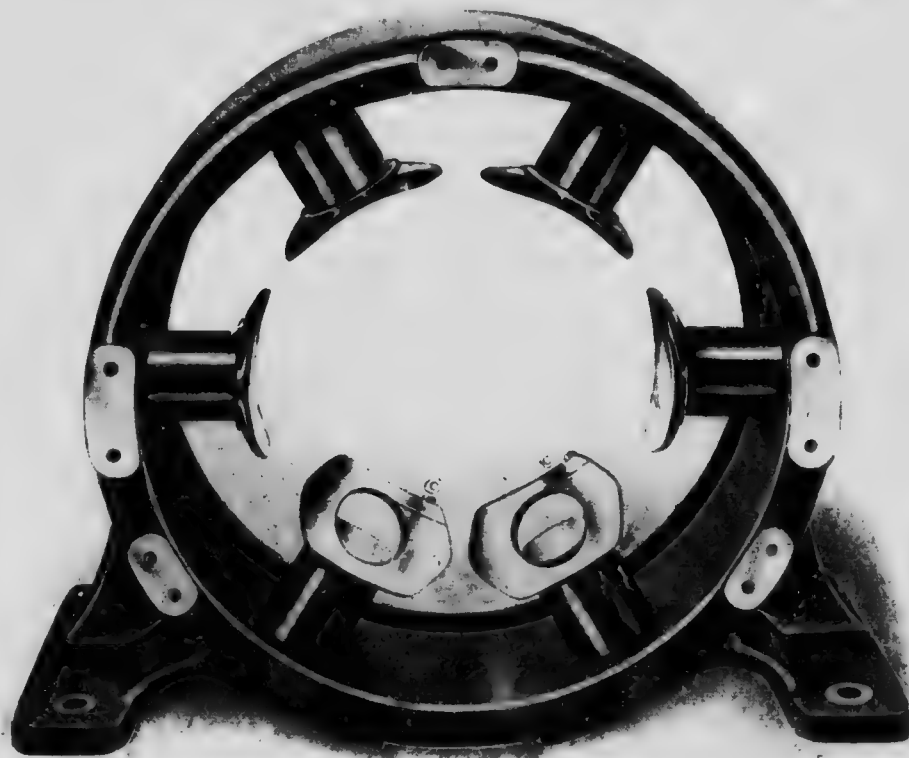


Fig. 599.—Field-Magnet Carcase of Slow-Speed Motor.

manner shown at c.c. The shape of these cast-iron extensions should be carefully noted, and how they bring the field-flux gradually down to a narrow gap to supply the reversing fringe for commutation. Laminated poles are not used, for it is claimed that the form of teeth used in the armature is such as not to give rise to eddy currents in the solid pole faces. These teeth are shown in Fig. 57, which depicts the carcass of the armature for one of these motors; the teeth, it will be noticed, overhang the slot from one side, and this spreading of the iron distributes the dense flux

passing through the tooth sufficiently well to avoid eddy currents in the poles. Owing to the slow speed, an abnormal amount of space has to be given to the copper, compelling the designer to use very narrow teeth. Wrought iron was deliberately adopted for the magnet cores in preference to cast steel, because at low flux densities its permeability is much higher (see Fig. 253, Vol. I.). In these slow-speed machines in order to secure good regulation the magnetic material must carry only the low flux densities, at which the wrought iron is the more efficient material.

A group of magnet frames, in which the solid wrought-iron cores are cast-welded into a cast-iron ring which forms the yoke, is shown in Fig. 600.

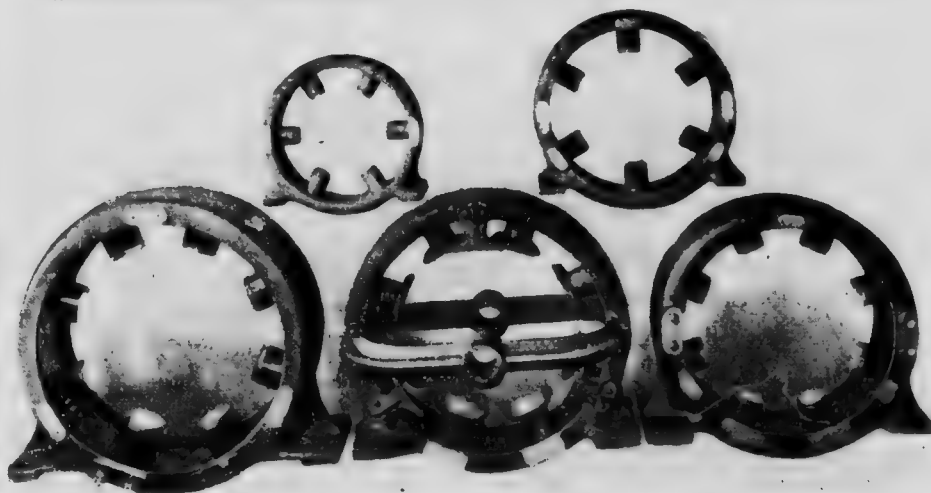


Fig. 600.—Magnet Frames of a Line of Slow-Speed Motors, $\frac{1}{2}$ to 5 B. H. P., 100 R. P. M.

The sizes run from $\frac{1}{2}$ to 5 B. H. P. at 100 R. P. M., but the outputs are correspondingly higher at higher speeds. By using a core of circular cross-section it is claimed that not only will less copper be used (as explained at page 23) for winding on a given number of magnetising turns of given gauge than with any other form of cross-section, but that there is a substantial saving in copper as compared even with multipolar machines with a single exciting coil.

III.—FURTHER DETAILS OF CONSTRUCTION

The various details in the construction of continuous current motors have, to a great extent, been dealt with already in the sections on the construction of the similar parts of continuous current generators. The reader will, by this time, have gathered that the chief differences between the ordinary modern machines for the two purposes is one of size, and

that, where no special conditions of running have to be provided for, a generator and a motor of corresponding output are almost identical machines. In this section, therefore, the additional details given are not meant to be exhaustive, but should be read in conjunction with the corresponding sections on generators.

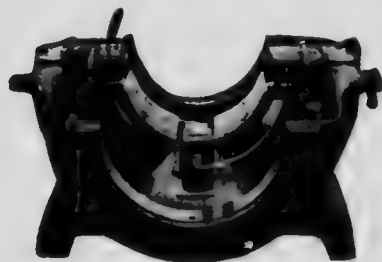


Fig. 601.—Half of the Magnet Frame of a 'Witton' C. C. Motor.

Field Magnets.—The details of the field magnets of several typical motors have been fully given in the preceding pages of this chapter, but as an additional example Fig. 601 shows the lower half of the magnet frame of the standard four-pole motors built by the General Electric Company, at Witton, near Birmingham. The yoke

which forms the outer casing of the machine is made of fine-grained cast-iron into which mild steel magnet cores are cast. These cores terminate at the air gap in pole shoes built up of laminated sheet iron fixed on the cores by countersunk screws. As usual the pole shoes are wider and longer than the cores, and provide support for the magnetising coils. Interpoles are also added for reasons already given, and the large space at the rear end of the figure is provided to accommodate the commutator and brush gear. The external appearance of these motors is shown subsequently (see Figs. 621 to 624).

As in some types of dynamos, so in many types of motors, considerations of space render the design of the magnetising coils a matter of importance. The underlying principles have already been discussed in connection with dynamos, and it will suffice to illustrate here two typical coils, one for the main field magnets and the other for the interpoles. In Fig. 602 there is depicted the pattern of a magnetising coil used by the Lancashire Dynamo and Motor Company, Ltd., for the main (shunt) excitation of the motors described on pages 585 and 591. In these machines the cores are circular or elliptical, the former (see page 23) requiring the smallest quantity of copper for a given iron section. The field coils, as is now almost invariably the custom, are former wound with

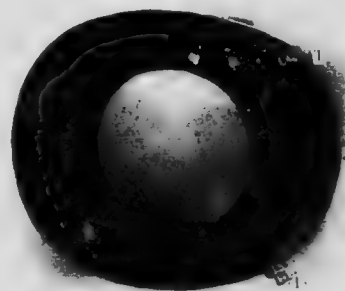


Fig. 602.—Field Coils of 'Lancashire' C. C. Motors.

double cotton-covered wire. They are then sewn with string, and impregnated with a special insulating compound under reduced pressure in a vacuum chamber, and afterwards thoroughly dried in special ovens. In this case each shunt coil is provided with its own special terminals $\tau \tau$, instead of leaving loose wires projecting and running the risk of being broken off.

For the interpoles, where space is, if possible, still more valuable, and where the windings have to carry the heavy series current, the same company uses strip copper, as shown in Fig.

603. It will be remembered that the cores in these cases have a narrow cross-section, and do not always extend across the whole length of the armature iron. This explains the comparatively narrow opening shown in the figure. The method of insulating and finishing the coil is similar to that just described.



Fig. 603.—Interpole Coils of 'Lancashire' Motors.

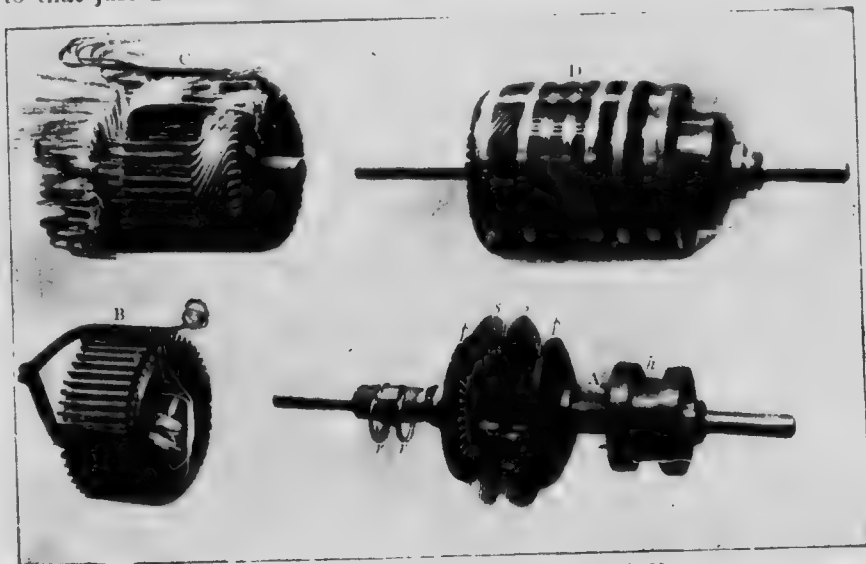


Fig. 604.—Details of the Armature of a Peebles Four-Pole Motor.

Armatures.—The stages of the process of building up the armature of a four-pole motor of 20 B. H. P. are clearly shown in Fig. 604, where the parts

illustrated below, is a motor constructed by Messrs. Bruce Peebles and Co. to give the above power when running at 700 R. P. M. on a 460-volt circuit. At A we have the shaft with the armature spider and the end plates *p* in position, and two of the stampings *s s* slipped on; the shaft also carries the hub *h* upon which the commutator is to be built and the bearing lining and lubricating rings *r r*. At B the armature core is shown complete and apart from the shaft, with the two first "former"-wound coils in position to start the winding; the shape of the slots and the insulating lining can be clearly seen. At C the winding is nearly completed, but in comparing with B it should be noted that the armature has been turned round. Finally, at D we have the completed armature with the binding wires,



Fig. 605.—Commutator for Westinghouse Motors.

which are rendered necessary by the straight-sided slots of the core, in position both on the core and the end connections. The over-all cylindric length of the finished armature at D should be compared with the length of the core at B, and the great increase of length necessitated by the cylindric shape of the end connections noted. This increase of length requires a corresponding increase in the size of the bed-plate and the over-all dimensions of the machine, but this disadvantage is considered of less consequence than the advantages gained in ease of construction, accessibility of the windings, and in other directions.

Commutators.—The details of the construction of several types of commutators have been given very fully in the dynamo section, especially with reference to large and to high-speed machines. Some commutators for small machines have there been illustrated (*see* Figs. 123 and 124), and in this chapter in connection with other matters cross-sections have incidentally been given of commutators for various sizes of motors. The reader should refer to these and examine in detail the methods used to insulate the copper bars, and to mount the whole securely on the shaft. In Fig. 577 he will find particulars of the commutator of the "Peebles" motors; in Fig. 580 particulars of the Brush "H.C." commutator; and in Fig. 593 particulars of the Crocker-Wheeler commutator for small bipolar motors. The commutator shown in Fig. 605 is designed by the British Westinghouse Company for a line of motors giving from $1\frac{1}{2}$ to $6\frac{1}{2}$ H. P. at speeds varying from 470 to 1,800 R. P. M. In Fig. 606 is

illustrated the finished commutator of the General Electric Company, Ltd., as used in the "Witton" motors.

It is absolutely necessary that the commutator, the weakest part of the machine, should be very substantially built to withstand the rough usage of motor work, and both in design and construction this condition is fulfilled in the commutators shown. Methods of assembling and details of manufacture (see pages 143 to 146) have already been described. Another point is the supply of an ample depth of copper to prolong the life of the commutator as long as possible. In the case of the "Witton" commutator of Fig. 606, a wearing depth of from $\frac{1}{4}$ inch to $\frac{1}{2}$ inch, according to the size of the motor, is provided. It would seem desirable to supply the greater wearing depth for all sizes, except where considera-



Fig. 606.—Commutator for "Witton" Motors.

tions of space render it impossible, for the rate of wear can scarcely be regarded as depending much upon the size of the motor. The British Westinghouse Company provide a wearing depth of $\frac{1}{4}$ in. to 1 in., according to the size of the machine, and the Brush Electrical Engineering Company in their H.O. Motors (see page 589) provide $\frac{1}{4}$ in. for the two smaller sizes, 5 to 20 B. H. P., and $\frac{1}{2}$ in. for the larger sizes, 10 to 100 B. H. P.

Brushes and Brush Holders.—In this connection also the details described in the dynamo section (see pages 146 to 154) are relevant, and the reader should not neglect to refer back to them. A few further details are added.

Brushes.—The relative merits of copper and carbon brushes have already been discussed; for motor work the use of the latter has become almost universal, especially where the motor may be called upon to run in either direction. The ensuring of a good conductive path between the actual brush and the metal of the holder has been mentioned as one of the difficulties in the use of carbon brushes, and it has been mentioned that a stranded flexible wire is now usually employed to bridge the gap.

There remains, however, the difficulty of attaching this flexible to the carbon with a good electric joint. The method used by the British Thomson-Houston Company, Limited, is shown in Fig. 607, which shows a carbon block with flexible attached. The attachment is made by a rivet which clamps the ends of the strands to the carbon, the upper part of the brush, shown light in the figure, being



Fig. 607.—Carbon Brushes for B.T.H. Motors.

afterwards turned to ensure good metallic contact being obtained. The flexible itself is, of course, of ample cross-section to carry the current which the brush is intended to collect.



Fig. 608. Siemens Motor Brushes.

In Fig. 608 is shown an ingenious device employed by Messrs. Siemens Bros. to increase the conductivity of the joint. In this case two brushes, instead of one, are used in each holder. Each brush carries at its top a metal clamp to which the flexible is attached. By, as it were, splitting the brush into two and providing a flexible for each part, the carrying power of two caps and two flexibles is secured, thus increasing the total conductivity without increasing the brush contact surface and the friction.

A very ingenious composite, or duplex, brush used on the Lundell motors made by the J.-L. Manufacturing Company, Limited, is shown in Fig. 609. The rubbing surface is provided by two carbon blocks *a* and *b* separated by a wedge of brass; these carbon blocks are held loosely against the brass wedge, and are pressed down towards the commutator by a flat bowspring *s s*, whose two ends press the blocks forward and which can be set up by the nut *n* working on the radial screw. By using the same spring for both blocks any inequality of wear is taken up. Additional details will be found in Fig. 618. The reasons for this complicated construction are interesting. The function of a brush is twofold: in the first place it has to convey the current from the commutator to the fixed external circuit, or *vice versa*, and for this purpose the device used should be of the highest possible conductance:

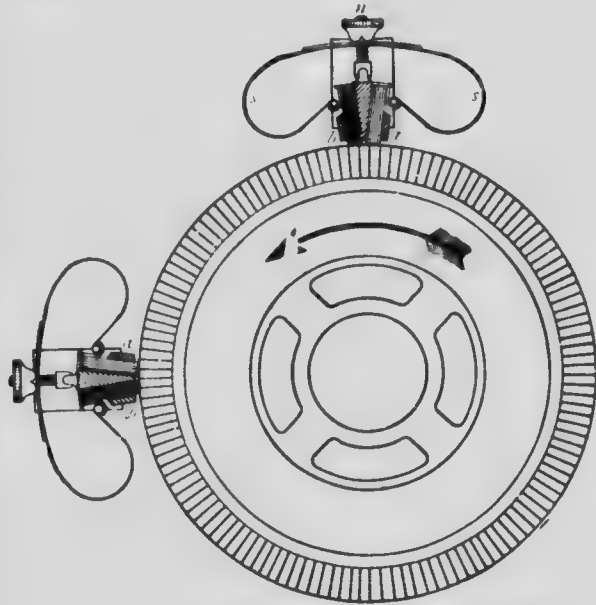


Fig. 609.—Composite or "Duplex" Brush for Lundell Motors.

On the other hand, the brush has to provide a path for the current in the coils during the commutating period when these coils are short-

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circuit, as it is called, by the brush. For this purpose, as has been explained in dealing with commutation, experience has shown that it

better for the brush to have an appreciable resistance instead of being an absolute short-circuit. The perfect brush should, therefore, have high conductance radially and high resistance at right angles to the radial direction. The conditions are, of course, antagonistic, but the brush shown attempts to satisfy them partially, inasmuch as the carbon block *a* is made of carbon of the highest conductivity, and the block *b* of carbon of the lowest conductivity procurable. Thus the block *a* is designed to carry most of the external current, whilst block *b* and the two surfaces between carbons and brass interpose a comparatively high resistance in the path of the so-called short-circuit currents. The carbon blocks are supplied by the firm "Le Carbone."

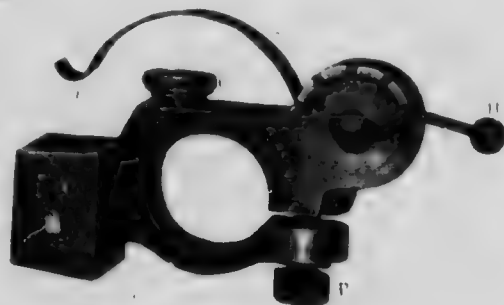


Fig. 610.—Brush Holder for British Thomson-Houston Motors.

Brush Holders.—In addition to the brush holders previously described (see pages 150 to 154), the following paragraphs describe some of those which have been more especially designed for motor conditions of working.

The British Thomson-Houston brush shown in Fig. 607 is used in the holder, Fig. 610, the brush being inserted in the box *B*, and the other end

of the flexible clamped under the screw *C*. The brush is pressed down on the commutator by the end *a* of the spring *S*, the right-hand end of which is coiled up and attached to the



Fig. 611.

Westinghouse Brush Holders.



Fig. 612.

axle operated by the handle *H*. By inserting the stiff wire *a* of the handle in one or other of the four notches shown, the pressure of the spring in



motors.

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the carbon block can be adjusted. The holder is clamped on the bar of the brush-rigging by the screw *p*. The whole arrangement is simple and

being strongly made, is well calculated to withstand the rough usage of motor work.



Fig. 613.—Brush Holder for Siemens Motors.

A very similar device (Figs. 611 and 612) for adjusting the pressure of the brushes is used by the British Westinghouse Company in their "Type G" motors. Fig. 611, which does not show the method of attachment to the spindle, is for machines up to 30 B. H. P., whilst Fig. 612 shows the form used in smaller machines.

The holder for the Siemens double carbon brush of Fig. 608 is shown in Fig. 613. The two parts of the brush are inserted side by side in a box which is held between substantial end plates, the other end of the flexibles being clamped to one side of the split block which is to be clamped on to the rod of the brush rigging. Pressure is applied to the upper end of the carbon blocks by the flat springs as shown, which swivel round the axle *a* and can be set up by a cylindric spring on the far side, a portion of which can be seen at *s*. The device is more complicated than the preceding, but is well designed to stand the conditions of actual work:

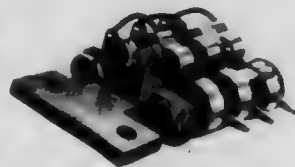


Fig. 614.—Brush Holders for "Lancashire" Motors.

The brush holder used by the Lancashire Dynamo and Motor Company, Ltd., is shown in Fig. 614. It is, like those just described, of the box

type, and the illustration shows three brushes attached to the carrier of the rigging. Strong coiled springs with a long range of adjustment provide the pressure on the back of the carbon blocks, and the usual flexibles are used to carry the current over. Further details of these brush holders will be found in Fig. 615.

Brush Gear and Brush Rigging.—Much of the apparatus already described under this heading for dynamos can be, and is, used for motors, but a few additional examples may prove of interest.

In Fig. 615 is shown the gear used for mounting the brush holders just described



Fig. 615.—Brush Gear for "Lancashire" Motors.

(Fig. 614) is being made by the Lancashire Dynamo and Electric Company, Ltd. A ring spring is along a diameter so that it can be clamped to the cylindrical bed of the bearing bracket of the motor carries four substantial arms or brackets on its outer periphery: Each holder, as shown in Fig. 614, is fastened to one of these arms by two set screws passing through a number of sheet-iron distance plates, by which it can be packed up and adjusted at any convenient height above the commutator. By removing one or more of these plates from time to time the wear on the commutator can be



Fig. 616.—Brush Gear for "Witton" Motors.

followed up without affecting the rigidity of the arrangement. Solid mica is used for insulating and being unaffected by heat or damp the holders cannot sag down on to the commutator. The corresponding brushes are connected by flexibles not shown in the figure:

The brush gear designed for the "Witton" motors by the General Electric Company, Ltd. is shown in Fig. 616. Instead of being of the box type, as in the last case, the gear is of the radial arm type, the carbon being firmly clamped in a sleeve on a moving arm, which is mounted so as to be free to turn on the brush-gear spindle. These spindles are mounted on a ring-shaped rocker from which each is insulated by an insulating bush specially moulded to the required shape, or by loose bushes and washers. The brushes are pressed towards the commutator by flat steel springs, and the bad electrical joint is bridged by the usual flexibles. The terminal flexibles are shown in the figure, and also the paralleling flexibles between the brush spindles of the same polarity.

Instead of clamping the rigging on the hub of the machine, it is sometimes mounted on other parts of the end bracket. In Fig. 617 is shown the end bracket of a line of British Westinghouse motors rated up to 75 B. H. P. In this the brush rigging is mounted on the arms of the bracket and the arrangement for rocking can be readily made out.

As a final example of this type of rigging, Fig. 618 depicts the brush gear designed to mount the duplex brushes (Fig. 609) of the Lundell motors: They are mounted on a four-armed spider or rocking ring which is cut so that it

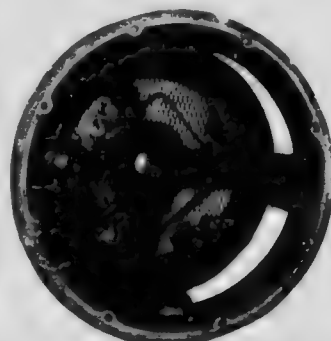


Fig. 617.—End Bracket of Westinghouse Motors, 8 to 75 B. H. P.

can be clamped on the motor in the usual way. The brushes and brush holders already described are mounted on the ends of the arms in shallow



Fig. 618.—Brush Gear for "Lundell" Composite or Duplex Brushes.

V-grooves which permit of bodily adjustment in the radial direction to allow for the wear of the commutator. The holders are, of course, well insulated from the arms, and holders of similar polarity are connected by the circular flexibles shown in the figure.

In small motors simpler methods of mounting are adopted, and rocking devices are frequently omitted. The end bracket (Fig. 619) for certain British Westinghouse motors up to $6\frac{1}{2}$ B. H. P. carries a simple spider for the brushes, not differing in principle from some of those already described.

The methods used by the Crocker-Wheeler Company for their small motors, not only for mounting the brushes, but also for bringing out the terminals, are particularly interesting. These methods can be fairly well made out by comparing Figs. 592 and 595, but to make them clearer Fig. 620 shows the inside of the end shield used for their "Form L" motors. The shield carries four porcelain bushings through the axes, of which conducting bolts or studs pass from the outside to the inside. The outer ends of these are provided with nuts to which live conductors can be attached, and on the inside two of them carry the brush-holders; the other two studs make connections to the field circuits, and as both field and armature connections are thus brought out, full facilities are provided for using both starting and controlling devices. It is claimed that the simplicity and ruggedness of the brush rigging is particularly well adapted for the severe conditions to which these small motors are often subjected.



Fig. 619.—End Bracket of Westinghouse Small Motors, $1\frac{1}{2}$ to 6 B. H. P.

IV.—MOTORS FOR SPECIAL PURPOSES.

Enclosed Motors.—As already pointed out, there are many positions in which it is absolutely necessary that the motor should be either com-

pletely, or almost completely, enclosed, so that it may be fully protected from the adverse influences of its environment. The dust, gritty and otherwise, which is inseparable from many industries would soon prove injurious to an exposed commutator, and especially is this the case where the motor has to be mounted beneath the floor of a tramcar or locomotive, and exposed to the dust and dirt of a not too-cleanly road. Then, again, motors may be placed in positions in which they are liable from time to time to be flooded with water, so that they require to be not only enclosed, but enclosed in a *water-tight* case. The driving of pumping machinery in some classes of mines is a case in point.

Further, in fiery mines the conditions may be even still more severe, and it may be necessary to make the case of the motor *gas-tight*, so that an explosive atmosphere may not be brought into contact with any sparks on the commutator, which would inevitably fire the gases and might start a destructive explosion.

Many types of motors have been designed to meet the special conditions which necessitate the enclosure of the motor. Most manufacturers so design their machines that it is possible to add on to their ordinary open-type motors extra casing, water-tight or otherwise, to cover the exposed parts which are liable to be injured. On the other hand, some manufacturers have faced the problem of the production of an enclosed motor as a special problem, and the enclosure of the motor has modified the electric, magnetic, and mechanical details of the design. This is specially necessary in the case of traction motors for tramcars.

The amount of enclosure required depends upon the necessities of the user. Often merely mechanical protection of the moving parts is sufficient and in these cases liberal openings for ventilation are left in the outer frames, such openings being frequently covered with perforated sheets of metal; they conduce materially to the cool running of the motor, and make it possible to run heavy overloads for longer periods. For some

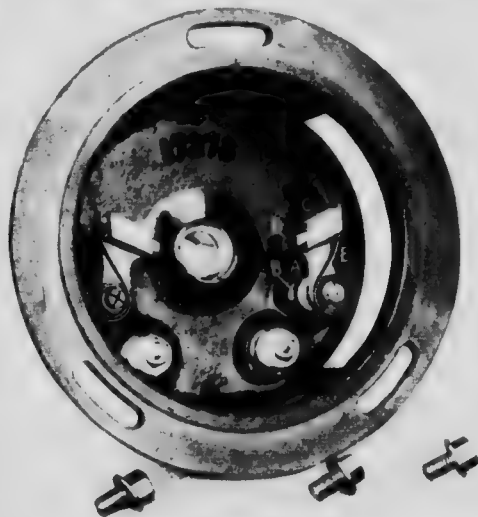


Fig. 620.—Brushes and Terminals of the Crocker-Wheeler Small Motors.

purposes more complete enclosure (for instance, to exclude gritty or other dust) is necessary, and then the ventilating openings have to be suppressed but the enclosing case is not made water- or gas-tight. In the most severe conditions, however, as indicated above, the enclosure must ensure perfect separation of the moving parts and the commutator from the outer atmosphere:

The subject of tramcar and locomotive motors is sufficiently important

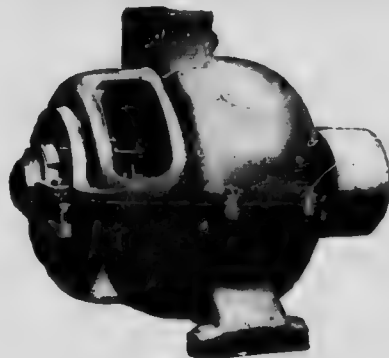


Fig. 621.



Fig. 622.



Fig. 623.



Fig. 624.

Various Types of the General Electric Company's Continuous Current Motors.

to deserve a separate section, but the demand for modifications of ordinary open-type motors to suit other special circumstances is extensive and such modifications, therefore, claim attention.

As one good example, from many which might be selected, Figs. 621 to 624 show the changes made in the ordinary type of "Witton" motor as manufactured by the General Electric Company, Ltd., to adapt it to some of the more special requirements of actual practice. In Fig. 621 is shown the ordinary standard type of motor variously described by different

manufacturers as the "semi-enclosed" or the "protected" type, since the bearings and their supports form a casing which protects the brush gear and the commutator from many kinds of accidental or wilful injury. In the next example (Fig. 622) the openings in the casing formed by the bearings have been covered with expanded metal doors which mechanically secure all the working parts from injury, whilst leaving free communication with the outer atmosphere for ventilation purposes. This type is, therefore, known as the "Enclosed Ventilated" type.

In Fig. 623 the expanded metal covers are replaced by solid sheet metal covers which completely close up the space containing the commutator and its fittings, the machine being described as "Totally Enclosed and Dust-proof." In the fourth example (Fig. 624), which is the "Water- and Gas-tight" type, whilst the general form is the same, the castings supporting the bearings have had to be modified so that properly machined and packed covers can be bolted to them, the joints being made both water- and gas-tight. It will be noticed that an annular plate has also been bolted on the commutator end round the bearing.

With variations in the details of design the method of using the same frame for "protected," "enclosed ventilated" and "totally enclosed" is in principle employed by many manufacturers. Some of the motors previously illustrated are so treated, and from this point of view attention is called to the Mather and Platt Motor (Figs. 573 and 574), the Peebles Motor (Figs. 577 and 578), the "Lancashire" Motors (Figs. 576 and 582), the Brush "H.O." Motor (Fig. 581), the Crocker-Wheeler Motors (Figs. 593 and 596), the Westinghouse Motor (Fig. 597) and several others.

Effect on Rating.—The various degrees of the closing up of the motors, as described above, have their effect on the rating of a motor of given weight or over-all dimensions. It has been shown (see page 581) that the full rated load of a particular motor depends in practice on the excess temperature at which the motor may be allowed to run for long periods of time, and it is therefore evident that if the facilities for ventilation are diminished the machine, at a given load, must get hotter. If, therefore, the previous temperature marked the limit permissible, the load must be reduced to keep within that temperature; in other words, the motor must be rated lower. Or putting it the other way round, a larger, and therefore more costly, machine must be provided to do the same work. In order, however, to keep the increase of size of the totally enclosed machines within reasonable limits, many manufacturers rate these machines to run at a somewhat higher temperature than those of the open or semi-enclosed type:

As an example, it may be mentioned that the "Witton" semi-enclosed and enclosed ventilated types (Figs. 621 and 622) are rated for a temperature rise at full load of 70° F., but the totally enclosed type (Fig. 623) is allowed

to rise to an excess temperature of 80°F. , and the water- and gas-tight type (Fig. 624) to an excess temperature of 90°F. above the surrounding atmosphere. The two first-named, however, are not exactly equivalent, though the excess temperature limit is the same. In order to carry the same load the enclosed motor has to be run at 10 to 15 per cent. higher speed, which means, of course, that the currents in the armature and magnets are less for the same working pressure and that, therefore, the rate of production of ohmic heat is diminished.

Fan-Ventilated Motors.—The effect of thoroughly good ventilation on the rating of a motor—that is, on the load which it can carry without becoming too hot—is so important that it is very carefully attended to,

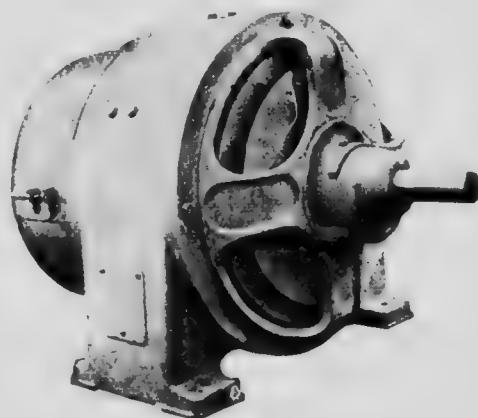


Fig. 625.—British Thomson-Houston Motor with Fan.

as the foregoing pages testify, in the details of internal design. With a spinning armature it is not difficult to ensure that air shall be driven through the machine by the action of the armature when rotating, and the effect is usually attained even with perfectly open machines. But when the machine is more or less enclosed the importance of passing a supply of cool air through the working parts is still further increased, and fan blades or complete fans are mounted so as to drive air through the machine.

A motor with such a fan is shown in Fig. 625, in which the motor appears with the shields at the pulley end removed so that the fan can be clearly seen. The motor is one of the British Thomson-Houston Company's standard motors, and is built in various sizes. The fan is a suction fan drawing air through the motor from the commutator end through an inlet on the underside of the shield, and discharging the warmed air at the pulley end.

Pipe-Ventilated Motors.—A still further development is necessary where the atmosphere in which the motor is placed cannot be allowed access to the working parts lest an explosion might follow. In such cases if it be desired to pass cold air through the motor it is evident that the necessary air must be obtained from a clearer atmosphere at a distance. Hence has arisen an addition which most manufacturers are prepared to make to their standard totally enclosed motors in the form of fittings for connection to external pipe systems through which the clear, cool air can

be drawn from a safe place and, if further deemed necessary, the heated air, after passing through the motor, can be discharged at a distant spot.

Such a "pipe-ventilated" motor, as made by the British Westinghouse Electric and Manufacturing Company, is shown in Fig. 626:

At the commutator end can be seen the opening A flanged for the reception of an inlet pipe, and at the pulley end two similar openings, B and C, for connection to an outlet pipe; one of these openings only is used in any given case, the other being closed with a plate, but it is well to have both openings

provided so that the most convenient one may be used. Cast-iron covers with a fan flar to that shown in Fig. 627. Cool, clear air is drawn in through the pipe, passes to the commutator enclosure and through the motor, to be discharged through one of the suitable openings at the pulley end.

Where the warmed air after passing through the motor can be safely discharged in the room, only one pipe-connection is necessary, as shown in the British Thomson-Houston motor in Fig. 627.

Motors for Rolling Mills.—

Perhaps the most severe conditions under which any motor can be called upon to work are those obtaining in rolling mills. The variations of load are probably more



Fig. 626.—Westinghouse Pipe Ventilated c. c. Motor.

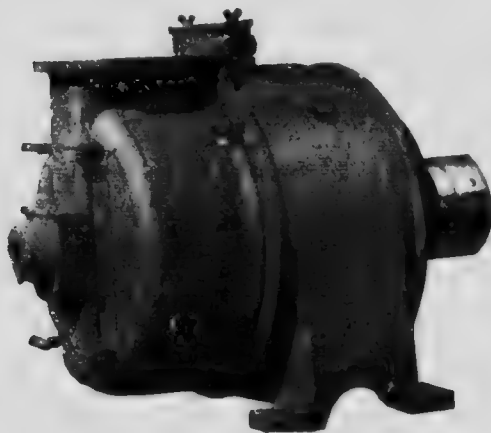


Fig. 627.—British Thomson-Houston Pipe-Ventilated c. c. Motor.

sudden, frequent, and violent than in any other heavy mechanical set of operations, and are such that they have taxed the ingenuity of engine-builders to design engines to fulfil their very onerous conditions. It will therefore, be interesting to examine an electric motor specially designed for this work which it successfully accomplishes:

The motor referred to is one designed and manufactured by the Crocker-Wheeler Company. The frame is in two parts readily detachable from one another, and these two parts are shown separated in Fig. 628. At the first glance it is obvious that the motor has been designed on the lines of the traction motor, where some of the conditions of working are similar but not so severe as in rolling mill. The external appearance of the motor closed up and complete is seen in Fig. 629. As would naturally be expected,

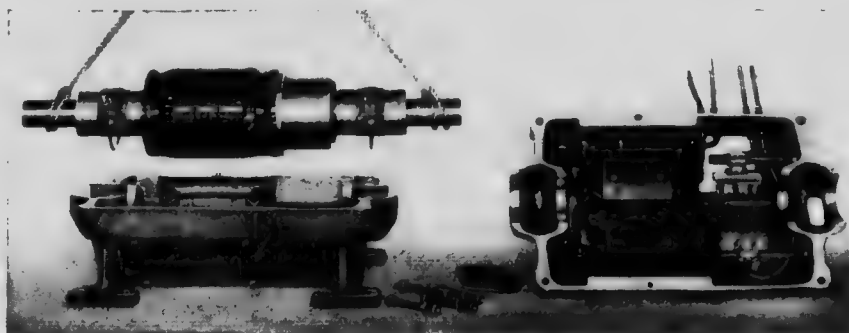


Fig. 628.—Crocker-Wheeler Motor for Rolling Mills.

the chief mechanical feature of the motor is solidity and strength to withstand sudden and violent strains. The frame is of steel, octagonal in shape, and cast, as already mentioned, in two halves. The lower half stands upon four feet which are cast on it, each at one of the extreme corners, and so placed in order that the spread of the supports may be as wide as possible. Each foot is pierced for two holding-down bolts. The two parts of the frame are held together by four bolts, one at each corner, and the electrical connections between the two halves of the machine are brought to the outside, so that by disconnecting these and the four corner bolts the top half can be lifted right off and all the interior parts quickly exposed for inspection.

In regard to the electrical and magnetic parts of the machine, the armature stampings are directly keyed on to the shaft by a substantial key, no intermediate spider being used. In this way, at the sacrifice of some ventilation facilities, great rigidity is secured for the drive through the armature laminations to the shaft, and the shaft itself can be removed and replaced with comparative ease. There are the usual ventilating

ducts between the laminations, two of these being shown in Fig. 628. The windings are simple and substantial, the insulation used being fire-proof. The conductors lie below the outer surface of the iron, and are held in their places by non-magnetic bands and wedges. The commutator is mounted upon a sleeve projection of the armature-core end flange—a method of construction which enables the shaft to be removed without disturbing the commutator. It is substantially built, as was to be expected.

The magnet cores are solid, and part of the frame casting, but the pole shoes are laminated and are each bolted to the core by two bolts. The air gap is wide to counteract the effect of the wear of the bearings, and to assist commutation. The brush holders are carried on spindles bolted to the frame, the nuts being accessible from the outside and, as in traction motors, there are only two brush spindles, although the machine is four pole. The brush holders, etc., have the substantial construction described elsewhere (see page 614) for the productions of this firm.

As in traction motors, the field coils are series-wound, but as the motor might at some time be in a position never arising in traction work—namely, under absolutely light load with full pressure on, a shunt winding is added which, by providing the necessary field, will cut down the speed which otherwise would become very high. This winding is such that the motor cannot run at more than double its normal speed if the load be removed.

The motors are built in standard sizes from $6\frac{1}{2}$ to 200 B. H. P., and as an indication of the size, it may be mentioned that the feet of the 200 B. H. P. motor cover a floor space $51\frac{1}{2}$ inches long (exclusive of shaft projection) and $37\frac{1}{2}$ inches wide, and it stands $35\frac{1}{2}$ inches high. Other examples of rolling-mill motors will be referred to in dealing with this particular application.

High-Voltage c. c. Motors.—Attention may be called here to the motors designed for use on high-voltage continuous current transmission systems. One of these, designed to take current at 5,000 volts, has been illustrated (Fig. 192) and described at page 197 in connection with the special regulator for shifting the brushes as the load is varied. The motor, which is a 300-kilowatt machine, was designed to absorb with two other similar machines the power received through the high-voltage C. C. trans-



Fig. 629.—Crocker-Wheeler Motor for Rolling Mills.

mission line at the Ironbridge sub-station from the Willesden generating station of the Metropolitan Electric Supply Company, Limited.

V.—CONTINUOUS CURRENT TRAMCAR TRACTION MOTORS

One of the most interesting, if not the most interesting, of the developments of the continuous current enclosed motor, is that which has been evolved for the driving of electric tramcars and electric trains. The problem to be solved was a difficult one, and many of the difficulties must have seemed wellnigh insuperable to the early pioneers. In the first place, in the case of tramcars, the motor has to be placed under the floor of the car, and

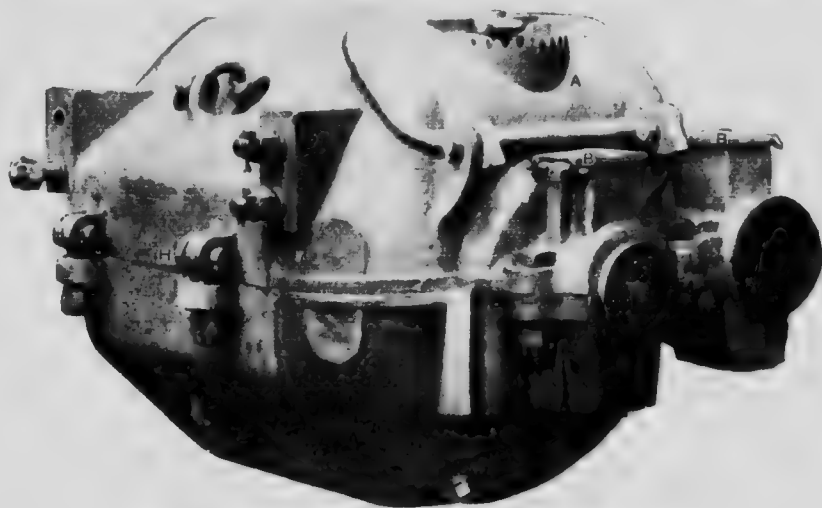


Fig. 630.—Brush Electrical Engineering Company's Tramcar Motor.

this floor cannot be raised considerably higher than in an ordinary horse-car. The vertical space available is, therefore, small. Further, the armature of the motor should have its axle at right-angles to the track, and in this position room must not only be provided for the armature core and the windings, but also for the commutator, the bearings, and the reduction gearing. On narrow-gauge tracks the space available for all these necessary parts is very small, and in some early designs the motor was placed with its axle parallel to the track and drove the car wheels through bevel gear which added considerably to the complexity of the machinery, and, as a consequence, to the risk of breakdown, besides absorbing a considerable amount of power. Within the confined space described the motor may have to develop from 25 to 100 H. P., and to be capable of standing very rapid changes of load from zero to a considerable overload in the course of a few seconds. Lastly, it is carried along within a few inches of the road

in all kinds of weather, and must therefore have its working parts perfectly protected from dirt, grit, mud, water, and other troublesome influences, which would quickly damage the electrical and mechanical components. This necessity for complete enclosure increases the difficulty of keeping the

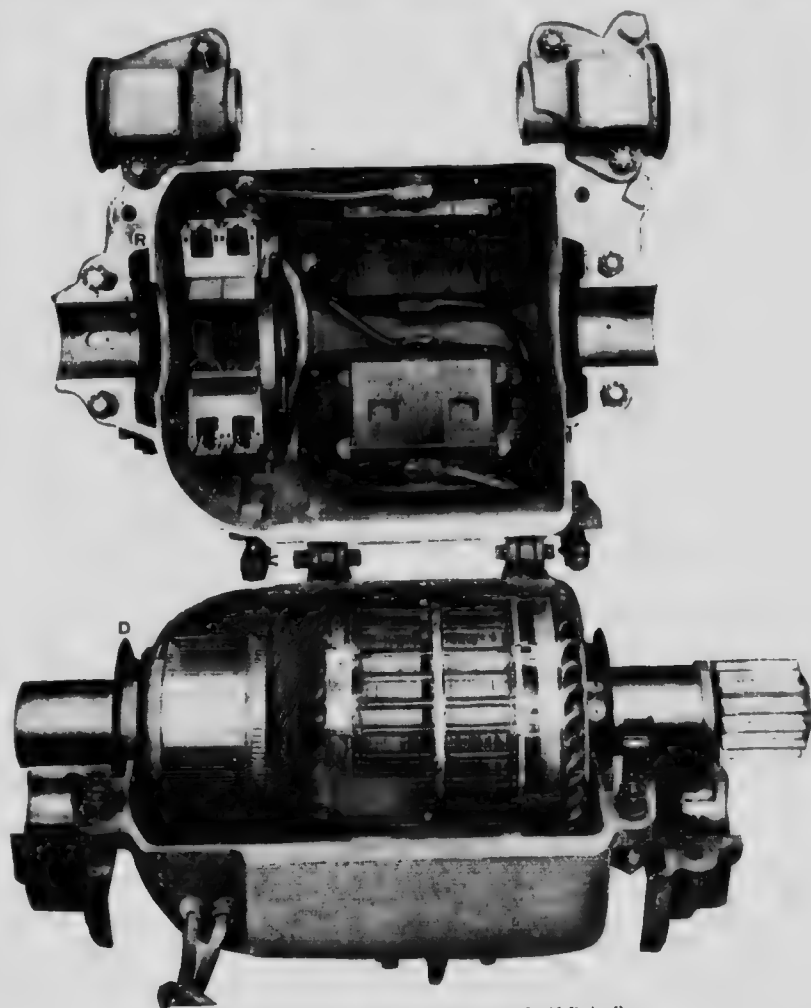


Fig. 631.—Brush Tramcar Motor (Upper Half Raised).

motor cool, for all energy lost electrically and magnetically appears as heat inside the motor case. All these and other conditions have been satisfied in the modern tramcar motor, and not the least remarkable result is the amount of power which it can develop in proportion to its weight,

for we find that small motors for light work will usually give one rate H. P. per 42 lbs. of dead weight, whilst the larger motors for heavier work are rated for the same amount of power for every 24 lbs. of their weight.

For tramcar work perhaps the first difficulty is one of speed, since there is not room for the large and heavy slow-speed motors described above, and ordinary electric motors run at speeds which make it impossible if the usual wheels are used, to build the armature on the running axle. For instance, if this axle were spun at a speed of 1,000 R. P. M., then, supposing the wheels to be only 21 inches in diameter, the speed of the car would

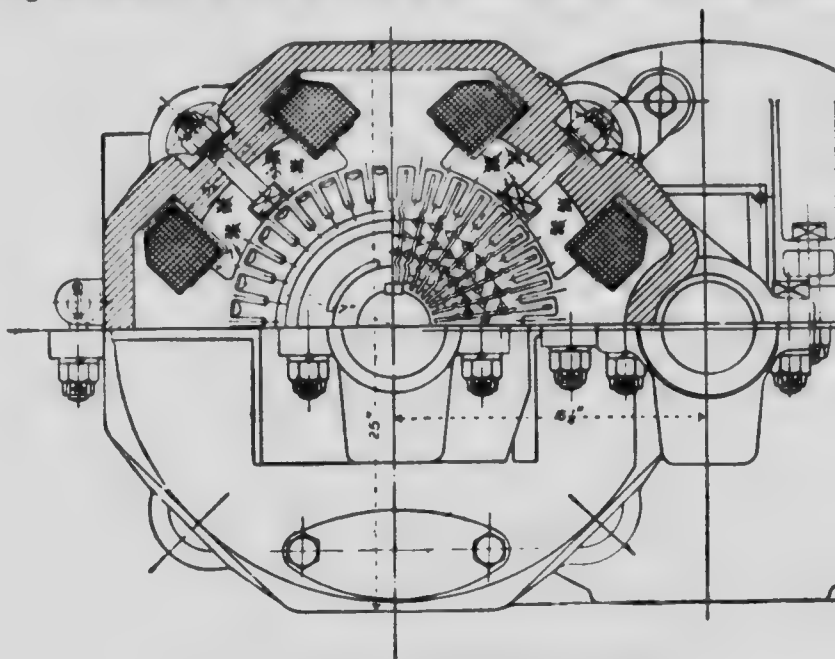


Fig. 63a.—End View and Section of Brush Tramcar Motor.

be over a mile a minute. Thus, if the motor speed were brought down to 500 R. P. M., it would still drive the car much too quickly for ordinary traffic. Some kind of speed-reduction gear is therefore absolutely necessary, and in some of the earliest forms the requisite reduction in speed was made in two steps by using a double-reduction gear. This was in the days when bipolar motors, not differing much from early generator types, were used. With the great modification in form shown in Fig. 569 (see page 509, Vol. I.), evolved about 1891, single-reduction gear, consisting of a single pinion and toothed wheel, became possible, and this method is now universally employed. For railway traction work reduction gear may be dispensed with altogether, and the running axle used as the axle of the armature

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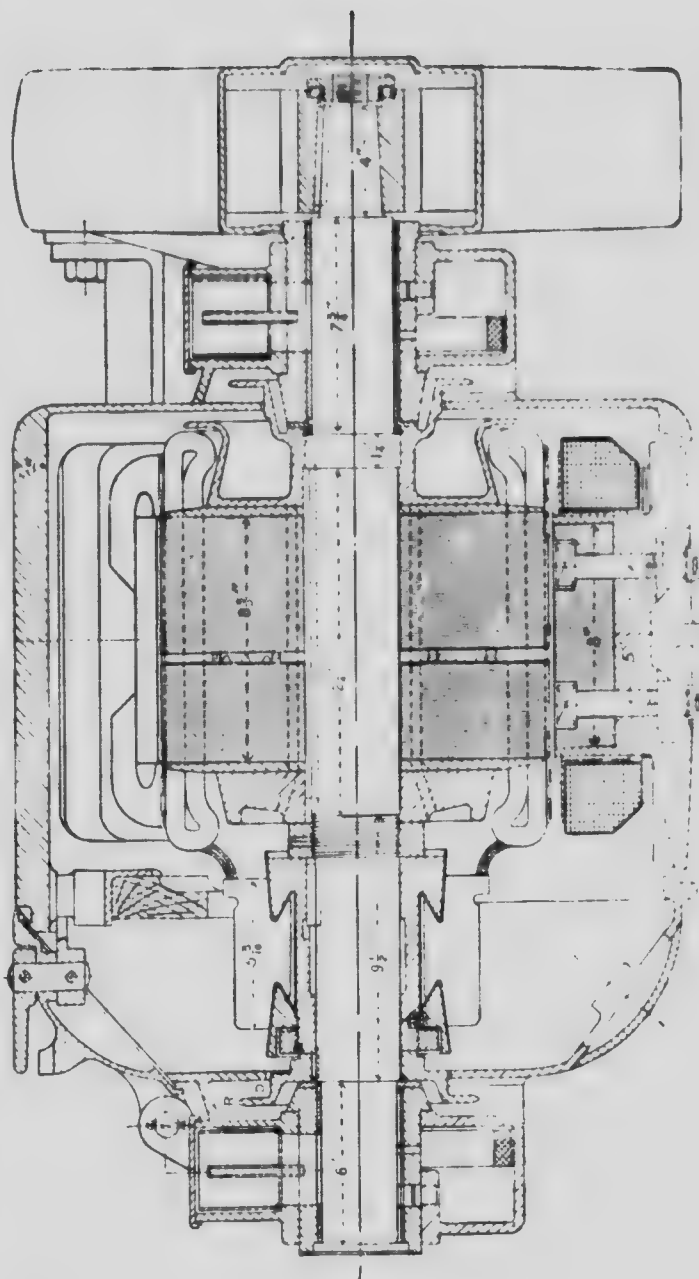


Fig. 235—Longitudinal Section of a Motor or Generator.

The outside appearance of the modern tramcar motor is shown in Fig. 630, which represents a 50 H. P. motor as built by the Brush Electric Engineering Company. All the working parts are enclosed by a water-tight case, but the brushes can be inspected by opening the cover A, whilst the covers B give facilities for inspecting the bearings and for lubrication. For more thorough inspection and repair the casing is in two parts hinged together at H H, the joint being carefully machined to ensure its being watertight. The end of the armature axle is seen at X, the second bearing C being for the axle, which carries the running wheels.

Electrically, the difference between modern motors and the earlier type shown in Fig. 569 (Vol. I.) is that the latter is a bipolar machine, whilst its successors are almost invariably designed with four poles. This is clearly seen in Fig. 631, which shows the Brush motor of Fig. 630 with the upper part of the frame raised, showing the two upper poles and other working



Fig. 634.—Armature of Brush Tramcar Motor.

Figs. 630 and 632. The surfaces where the core and the frame are in contact are very carefully machined so as to ensure a good magnetic joint, for these surfaces cut right across the magnetic circuit, as does the joint between the two halves of the casing which, therefore, must be carefully machined and fitted, not only because it has to be mechanically watertight, but also because it has to be magnetically good. The magnetising coils surround the cores, and are held in their places by the projecting polar tips and by special lugs which can be seen in the figure. These coils are first wound upon moulds and then carefully insulated, baked, and waterproofed before being placed in the motor. Further details of the motor are given in Figs. 632 and 633. The lower half of Fig. 632 shows an end elevation minus part of the gear case on the right-hand side, whilst the upper half is a cross-section perpendicular to the axle, and passing through the position of the nearer magnet bolts. It will be noticed that part of the magnet core is cast solid with the case projecting inwards about 1.5 inches. To this solid part of the core the laminated portion is bolted by two bolts (Fig. 633), the heads of the bolts, as can be seen in Fig. 633, being in a recess in the pole face, and the ends of the bolts, projecting into

parts. The outer frame or body of the motor is of cast steel, from which the cores and poles of the magnet project. The latter are laminated, being built up of sheet steel; when finished they are bolted to the frame by the bolts seen clearly in

recesses in the outer casing where are, easily accessible, the nuts and lock nuts for tightening up. The laminated portion held together by four bolts, is built up of stampings which towards the armature are extended to form the wider pole faces, and thus, incidentally, give the necessary projections for holding the magnetising coils in their places. The core is 8.75 inches long and 5.25 inches thick, this thickness being expanded to 7.25 inches for the pole face.

The armature has substantial teeth and rectangular slots in which the former-wound coils are placed in two layers, and held in their places by binding wires, which can be seen more clearly in Fig. 634, which depicts a finished armature of this make. There is one radial ventilating duct placed not quite centrally, but nearer to the commutator end, presumably



Fig. 635.—British Thomson-Houston Tramcar Motor, with Gear Case.

to allow the central binding wires to be placed midway on the core, the face of which is machined out to receive them. The distance pieces to the radial ventilating duct can be seen very clearly in the right-hand quadrant of Fig. 632; they project alternately two and one from the adjacent commutator plates. The over-all diameter of the armature is 14.25 inches, and the air gap is relatively large, a large air gap being necessary in this type of motor for both electrical and mechanical reasons. Electrically, it assists commutation, and mechanically, it tends to minimise the evil effects of decentering, to which attention has been called elsewhere. Such decentering will inevitably occur as the linings of the bearings wear away.

The details of the commutator construction can be made out from the section in Fig. 633, whilst the brushes, which it will be remembered, are to be placed 90° apart on the commutator are clearly seen in Fig. 631. The commutator is a substantial one, and has a working surface parallel to the shaft of about 3.5 inches, to enable a pair of brushes to be used on

each side. Attention should be called to the device intended to keep the lubricating oil from the bearings from reaching the commutator. It can be most clearly seen in Figs. 631 and 633 in the shape of an annular disc **D** which revolves in a recess **R** in the frame casting. A similar device is used at the pinion end of the shaft.

Exclusive of the gear case and pinion, the motor is 34 inches wide,

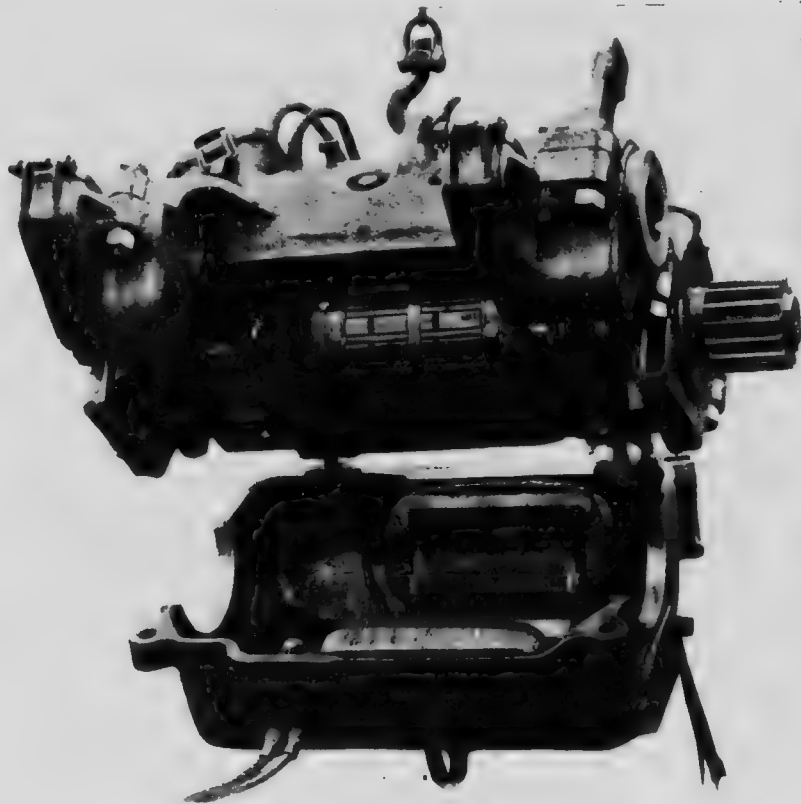


Fig. 636 — British Thomson-Houston Tramcar Motor.

37 inches long in the direction of the shaft and 25 inches high. It is designed for an output of 50 B. H. P. when running at a speed of 400 R. P. and supplied with current at 500 volts.

As another example of a well-known and widely used tramcar motor, Fig. 635 shows a tramcar motor with the gear case attached, built by the British Thomson-Houston Company. The substantial character of the construction, and especially the provision of amply massive bearings, will be evident on inspection. These bearings are all provided with large res

voirs for oil, easily accessible by the lifting of the covers *c c c*. The removable cover *B* is provided so that the brush gear and commutator may be inspected; *A A* are the leads from the brushes and *F* the leads from the field-magnet coils. The design of the brackets by which the removable gear-case is securely attached to the motor casting should be noted. The same motor is shown with the gear case removed and the lower part of the casing opened downwards in Fig. 636, the armature being sustained by the bearings in the upper part of the casing. It will be noticed that the massive screws fixing the cores and their attached pole faces to the frame do not show through on the latter; their heads can be seen at *s* and *s* in the preceding Fig. 635.

The armature is shown separately in Fig. 637. It is of the usual substantial construction, the teeth being particularly massive and few in



Fig. 637.—Armature of British Thomson-Houston Tramcar Motor.

number. The core is provided with two wide radial ventilating ducts for cooling purposes, and the former-wound coils are held in the wide open slots by bands of steel binding wires, three of which are on the core placed in recesses machined out. For reasons already fully explained, the segments of the commutator are very numerous in all these modern traction armatures. Five of these segments adjacent to one another have been marked with white radial lines; they are the segments belonging to the coil 1, marked with a white line. In other words there are five commutator segments per slot, the relative positions of the slot and its segments, about 45° apart, being as shown. The guard *G G* for keeping the lubricating oil from spreading from the bearings to the commutator is very clearly indicated.

In recent designs of traction motors interpoles have been introduced, notwithstanding the limited space which is available in what may be called the polar volume for any such additions. The conditions, however, under

which the motors have to work, especially if electrical braking is largely used, make such demands on the commutating arrangements that no device which would improve the commutation can be passed over if it be at all possible to introduce it. The action of interpoles on the commutation has been dealt with elsewhere (*see* pages 107 to 111), and we are now only concerned with their introduction into traction motors.

The problem of such introduction has been successfully solved by Messrs. Dick, Kerr and Co. Fig. 638 shows, with its gear case, one of their recent motors. Externally, it is not very different from the motors previously described, but it will be noticed that in addition to the bolts at A and A', which hold on the ordinary cores of the field magnets, there are shown the nuts of bolts at B for the attachment to the frame of the core

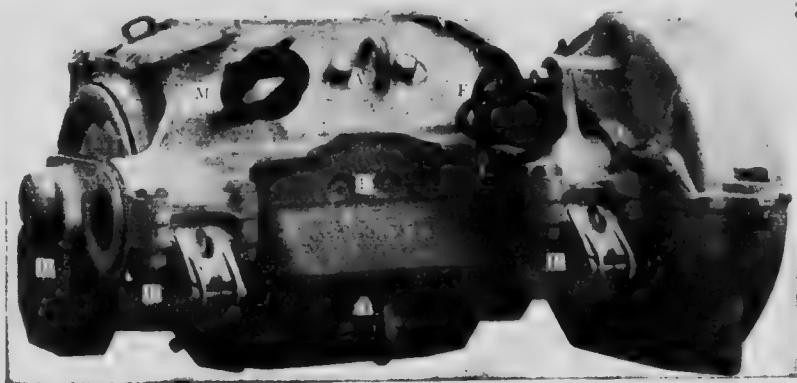


Fig. 638.—The Dick, Kerr and Co. (D.K.) Interpole Tramcar Motor.

of an interpole. These interpoles are of solid steel, and are fitted symmetrically between the main poles. Before leaving the external view it may be noticed that the armature leads are brought out at M, and the field magnet leads at F; the connection of the gear case to the motor frame should also be studied.

Further interesting details of this motor are given in Plate XI, in which will be found two views of the motor, partly in section, and partly in elevation, with a number of the principal dimensions added. The general appearance of the field magnets of the motor will be more readily realised from an inspection of Figs. 639 and 640, which show respectively the upper half and the lower half of the field frame, with the poles and excitation coils in position. Three of the interpoles, it will be noticed, are attached to the upper half of the frame, and the remaining one to the lower half; the details of the attachment of the cores, etc., of the two horizontal interpoles being more clearly seen in the right-hand figure of Plate XI. A com

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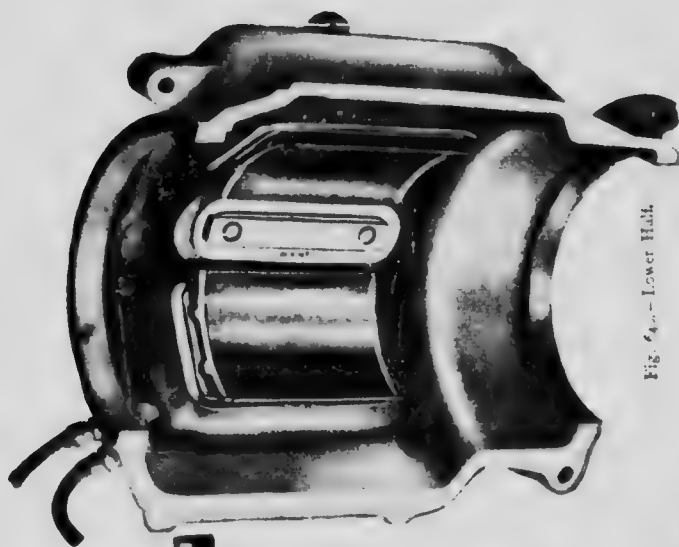


Fig. 632—Lower Half

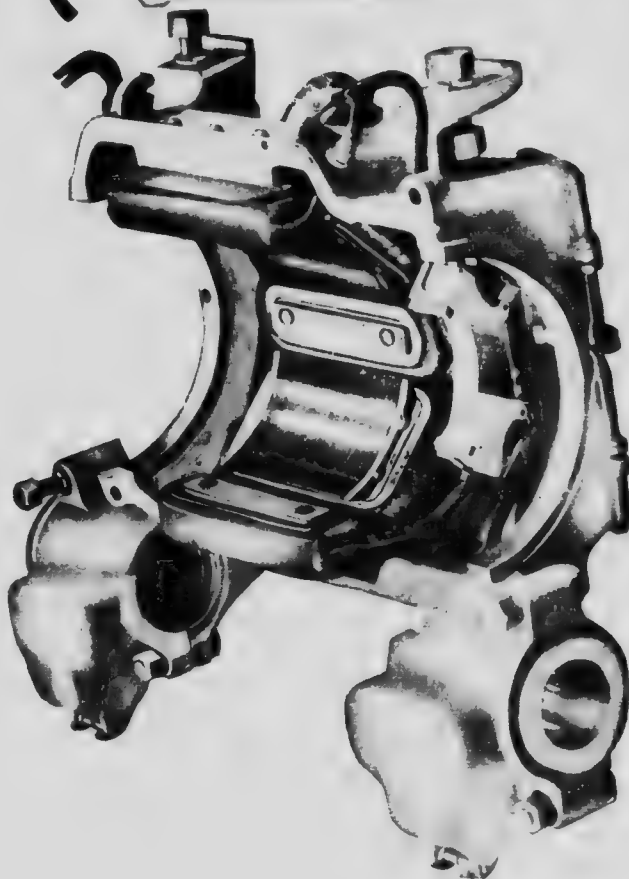


Fig. 633—Upper Half

Dick, Kerr and Co. Inverclyde, Transcar Motor.

parison of the section in the plate with Fig. 639 will make the method quite clear.

The cores of the field magnets (see Plate XI.) are laminated for a distance of 3 inches from the pole face, where they bed on to a solid but short core projecting $\frac{1}{2}$ inch inwards from the frame. These cores are about 10 inches long and $4\frac{1}{2}$ inches wide, the width being extended to form the pole face, which has a width of about 7 inches opposite the armature. The laminations are held together between substantial end plates by four bolts *bb* in each core. They are secured to the frame by substantial screws, $\frac{7}{8}$ inch in diameter, which do not penetrate as far as the pole face, which is thus left clear for the magnetic flux. The left-hand figure of Plate XI. is a vertical section through the axis and, with the other figure, gives full details of the interpoles which are built up of solid metal in several pieces to provide the necessary flanges for holding on the exciting coils, as well as the usual core and pole face. Each core, etc., is held on by two bolts; as shown, these bolts being tightened up from the outside.

The armature, which is shown separately in Fig. 642 is $13\frac{3}{8}$ inches in diameter, with a core 10 inches long, having 35 wide open slots, as shown in the right-hand figure of the plate, and with no radial ventilation ducts such as appear in the armatures previously described. The conductors are as usual, held in place by bands of steel wires in recesses machined out from the core. This core is built up of thin sheet-steel discs covered with insulating lacquer. The coils are former wound, and are covered in the first place with double cotton and asbestos, and then three coils being laid together, they are encased in mica with paper insulation, and afterwards covered with a thin webbing, the whole being dipped in a thin insulating compound and finally baked. Each separate coil end is indicated by a distinctive colour to facilitate it being connected up to the commutator. Many other interesting details, to some of which reference will be made later, are shown on Plate XI.

Mechanical Details.—It will be unnecessary to repeat much of what has been already set forth in considering interesting points of design in ordinary continuous current motors, so far as such details are true similarly in traction motors. The special conditions of service, here alluded to above, give rise to some minor modifications in design in addition to the major modifications already noted. A few of these modifications will now be referred to.

Shaft Driving.—Because of the sudden and great changes in load, the mechanical connection between the whole core and the shaft must be very rigid and strong, and the core and shaft, considered as a single unit, must be very substantial. This is well illustrated by Fig. 641, which represents the shaft and unwound armature core of a Westinghouse motor. Both slots and teeth are relatively large, and there are thirty-nine of each.

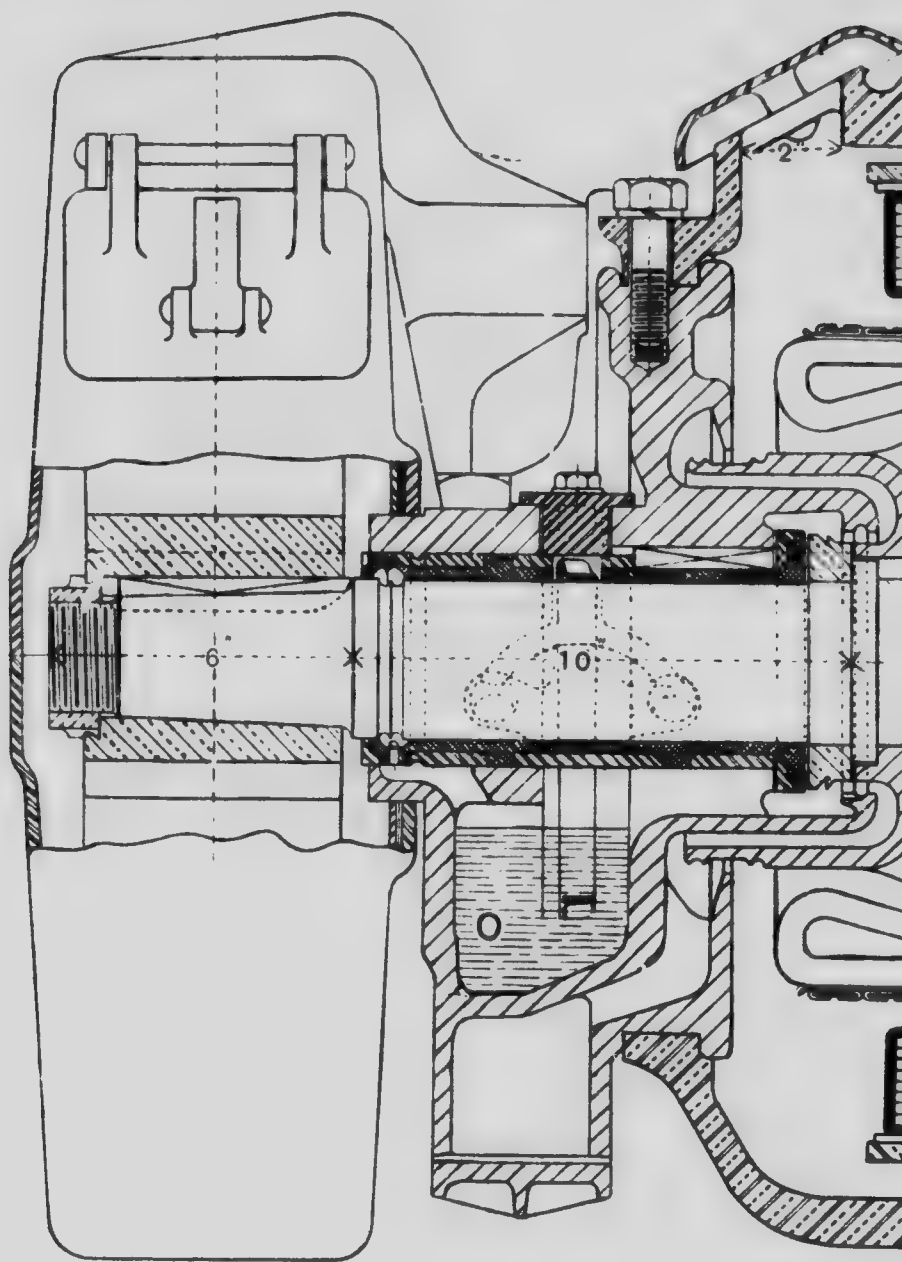
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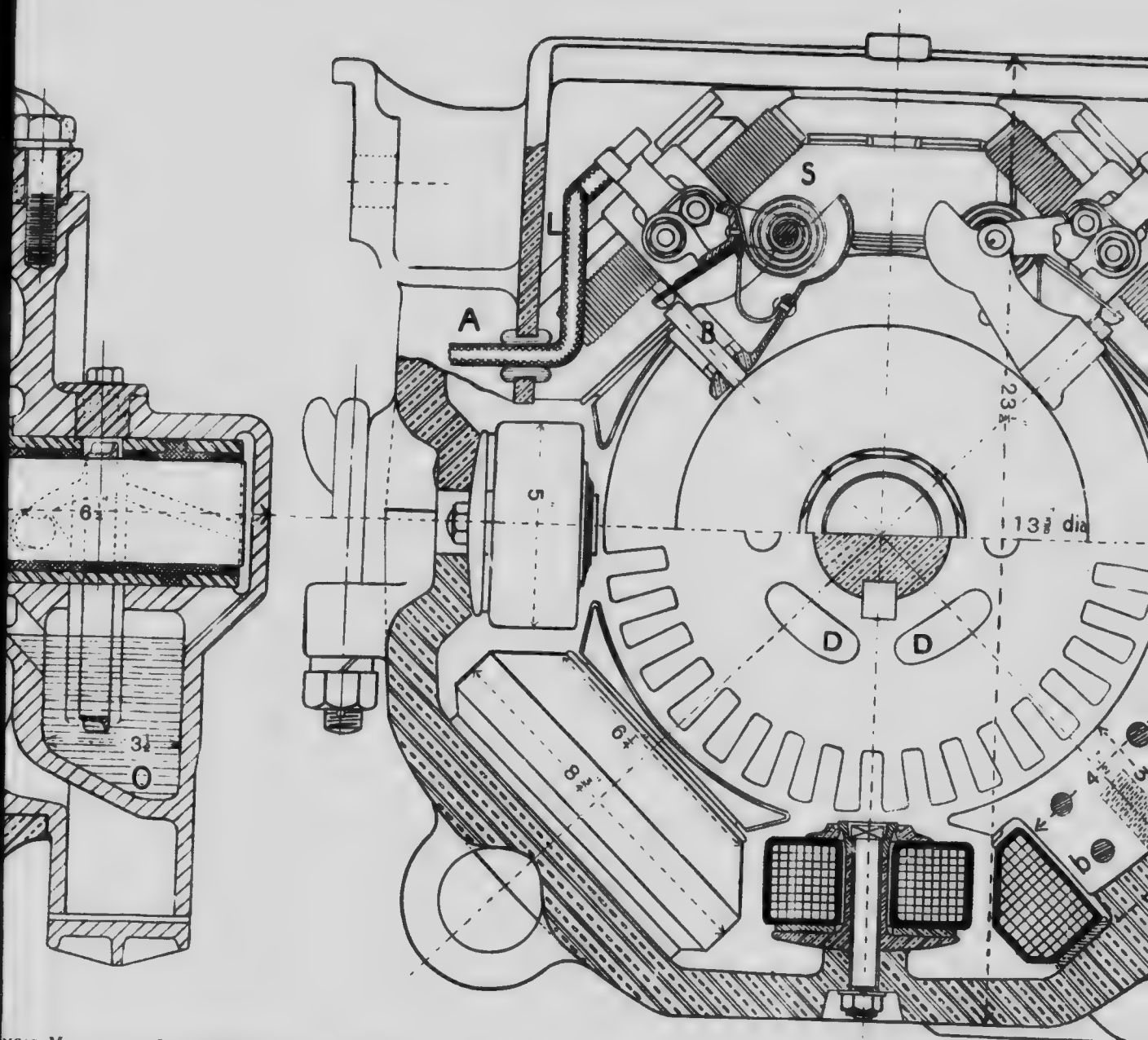
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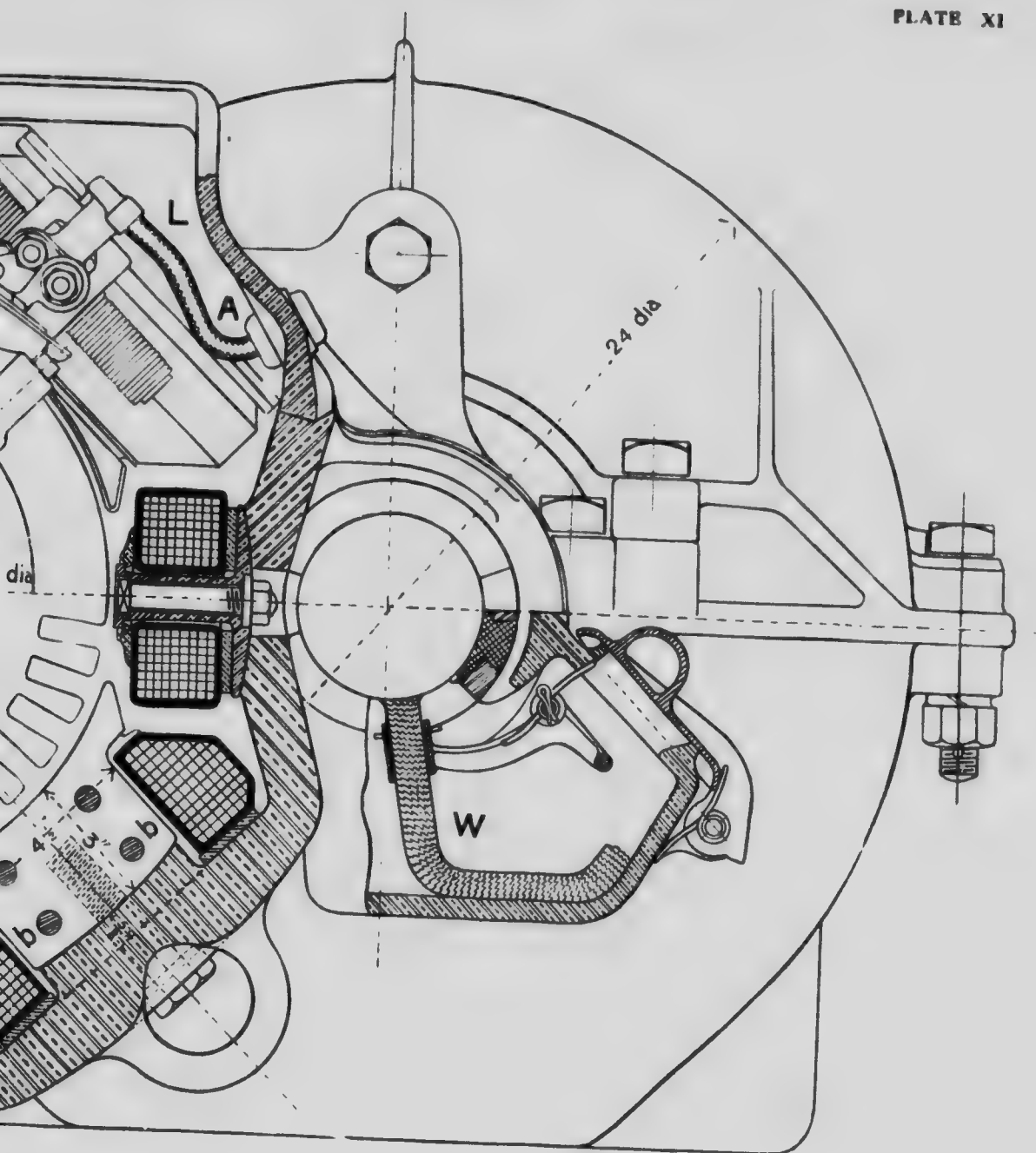
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SYNCHRONOUS MOTOR WITH INTERPOLES, 40 H. P. AT 500 R. P. M. AND 500-VOLT CIRCUIT

PLATE XI





It is, of course, further necessary for the safe driving of the motor by the copper conductors in which the driving forces are first developed, that these conductors should be held securely in their places. In the traction motors described above the slots shown in the various drawings are all wide open slots, and, as has been pointed out more than once, the conductors are finally held in their places by binding wires. The armature carcass in Fig. 642 is also designed so as to render necessary the same method of counteracting centrifugal forces. In this case the armature wires are, as usual, first wound on formers and are grouped in sets of three, insulated from one another, and with six ends brought out for connection to the commutator. Each set is carefully bound with a serving of insulating material and taped, varnished and baked before being laid in the slots, in which it is placed in the usual position. For the final binding wires, recesses are cut in the outer periphery of the core discs, as can be seen by inspecting the figure. These recesses are sufficiently deep to sink the outer surface of the binding wires below the general outer surface of the teeth, and therefore, even if the teeth through the wearing of the bearings should happen to touch the pole faces, these wires will not be damaged. In this motor there is a hand hole in the lower case through which the air gap can be inspected and, so as to guard against the above danger, the effect of the wearing of the bearings ascertained without dismantling.

Ventilation.—Traction motors being entirely enclosed, efficient ventilation becomes very difficult, and in many cases is confined to churning up the air inside and ensuring that it is continually driven through the parts of the machine in which the ohmic and other heat is being produced. This continuous circulation of the air through the armature and its discharge against the faces of the poles is secured in many cases by radial ventilating ducts. Attention has already been called to these ducts in



Fig. 641.—Armature Carcase of Westinghouse Tramcar Motor.

the case of the Brush motor (Fig. 634) and the British Thomson-Houston motor (Fig. 637). In the armature carcass of the Westinghouse motor (Fig. 641) the central ventilating duct can be clearly seen. In all such radial ducts when the armature is rotating the tendency will be for the enclosed air to move outwards, and if only proper longitudinal ducts are provided for the drawing in of cool air from the ends, efficient circulation will follow, especially if the spacing pieces necessary to form the ducts are shaped so as to assist the natural fan action of the rotating core.

In the Dick, Kerr motor (Plate XI.) there are, however, no radial ventilating ducts, as will be seen on an inspection of Fig. 642, which represents the finished armature. The ventilation of this armature is ensured by the fanning action of the connections between the armature coils and the commutator segments. The connections are made of thin sheet copper

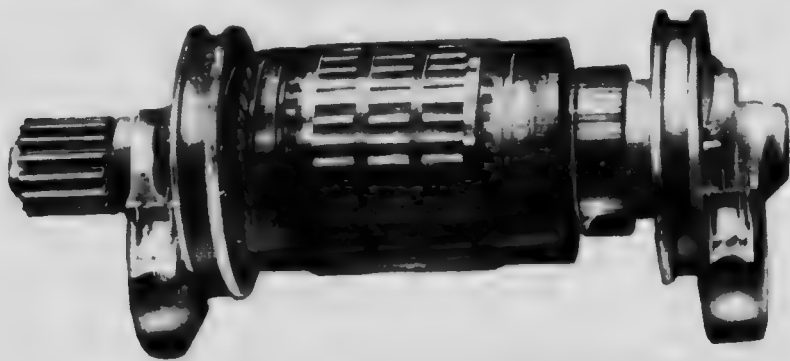


Fig. 642.—Armature of D.K. Tramcar Motor, showing Oil Reservoirs of Bearing Boxes.

strips, so shaped that when the armature rotates they act as fan vanes and draw air through the armature core from the gear end towards the commutator end. The air, however, is not simply churned round inside the motor for there are two small openings on the top of the shell, one at the gear end, through which air can enter, and the other at the commutator end through which some of the heated air can be expelled. A current of air is thus set up through the motor, which is claimed to be so effective that the motor runs fully 25 per cent. cooler than would otherwise be possible. The passages by which this air passes through the armature core are shown at D D in both figures of Plate XI.

Commutators.—The general principles of commutator design have already been fully dealt with, and the reader will have no difficulty in following the details of the commutator of the Brush traction motor shown in Fig. 633 and of the Dick, Kerr traction motor shown in Plate XI. Attention should be specially directed to the devices by which the different parts of the commutator are held rigidly together, and those by which

the whole commutator is rigidly connected to the other parts of the rotor of the machine.

An additional example of the commutator of a traction motor is given in Fig. 643, which is a line drawing partly in section and partly in elevation of the commutator of a British Thomson-Houston motor. It will be useful for the reader to compare the details of this drawing with those of the previous drawings referred to above.

Brush Gear.—The conditions of working also materially affect the design of the brush gear. In the first place, the brushes must, if possible, be fixed brushes, and no adjustment of lead or lag should be required at any load. Even without interpoles this condition has been satisfied in the modern tramcar motor, but with their aid the running has been made practically sparkless with fixed brushes under all ordinary loads. Then again the motor must be capable of running in either direction. Thus the brushes should be radial, and carbon brushes, in one form or another, admirably satisfy this condition.

Further, as the motors are four pole, the collecting points are 90° apart, but four sets of brushes need not be used for, as has been shown elsewhere, the armature windings can be so arranged that two sets of brushes only are necessary. This enables the whole of the brush mountings to be contained in one half, invariably the upper half of the shell—a most convenient arrangement, both as regards neatness of design and accessibility for maintenance.

The general method of satisfying these conditions can be gathered from Figs. 644 and 645, which give two examples of the Brush gear designed by the British Thomson-Houston Company for their traction motors. The position of such brush gear in the upper case of a motor can be clearly seen in the view of the open Brush motor in Fig. 631. The brush holders are securely bolted to the casing, but are, of course well insulated from it; they can readily be removed if required. In the details of the brush gear of the British Thomson-Houston motors shown

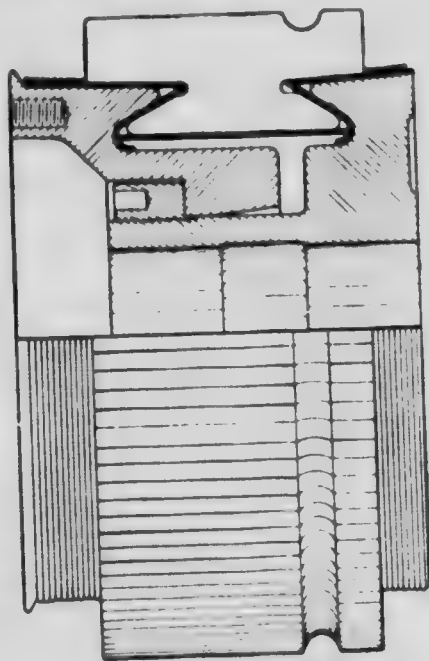


Fig. 643.—Commutator of B. T. H. Tramcar Motors.

in the figures can be seen the method of attaching the holders to the frame of the motor by a hard-wood base upon which they are mounted and which is bolted to the frame. Each holder carries two brushes independent of one another, each mounted on a spring finger made of bronze. They are adjustable parallel to the axis and also radially.

Further details for the mounting of traction-motor brushes are given in Plate XI. for the Dick, Kerr motors. Two views are given at the top

of the right-hand figure one in elevation and the other partly in section. The brush gear is not shown in the left-hand figure.



Fig. 644.



Fig. 645.

Brush Gears for B. T. H. Tramcar Motors.

Lubrication.—For motors which have to run for long periods in such inaccessible positions the details of the lubricating arrangements have to be carefully designed. In the examples already given attention has been called more than once to the reservoirs provided for the supply of oil to the bearings, and some of the drawings show the devices by which the circulation of this oil through the bearings is ensured.

It is also necessary that the gear wheel and pinion should be well lubricated, not only to diminish the wear on the surfaces of the teeth, but, in addition, to minimise the noise often produced when a large amount of power is being transmitted by toothed gearing. In modern traction motors the gears practically run in oil, as will be gathered from Fig. 646, which shows separately the gear case of a Dick, Kerr motor. In this gear case the reservoir for the oil is exceptionally deep and ample. The gears can be easily inspected when the lid L is lifted, and when necessary the top half of the case can be thrown open if the bolt B be withdrawn.

It is also very important that the oil should be prevented from pene-

trating to the commutator or to the inside of the motor, either by travelling along the shaft or by splaying or otherwise, and more than once the attention of the reader has been directed to the safeguards designed for this purpose. In the Dick, Kerr interpole motors the arrangements for preventing the oil from reaching the bearings are very thorough. The bearing boxes for the armature axle, as will be seen in Fig. 642, are solid castings, thus making the interior of the motor practically oil-proof. The castings are not only large enough to provide ample reservoirs for the oil, but also to allow loose ring lubrication (*see* Plate XI.), which is so common in fixed machinery, the oil, after use, being drained back into the reservoirs through channels in the linings of the bearing. It is claimed that these bearings can be run for a fortnight without re-oiling. The running axle bearings are lubricated by cotton wicks, the lower ends of which dip into the oil reservoir, the upper being pressed against the axle by springs.

Motor Gearing.—For

electric railway work it is possible to build the motor armature on the axle to which the driving wheels are attached, but the conditions of tramway service with its numerous startings, slowings-down, and stoppages, make it necessary to interpose between the armature and the

running axles some form of speed-reduction gearing. For such speed reduction, several forms of mechanism are in common use for other purposes. To mention the chief forms: there are spur gearing, worm gearing, chain gearing, belt driving, and friction clutches. Of these, though some of the others have been tried, ordinary spur gearing has survived as the most suitable for the various practical conditions of tramcar working. Such gearing can either be single-reduction gearing, double-reduction gearing, or still more complicated. In the early days of electric tramway work, when bipolar motors only were available, the economical speed of the motors was such that it was found necessary to devise double reduction gearing, i.e. gearing with two steps in the speed reduction, and necessitating two pinions and two gear wheels, with three rotating shafts. With the development of the four-pole traction motor, it was found that one of these steps could be dispensed with, thus leading to the single-reduction gear which

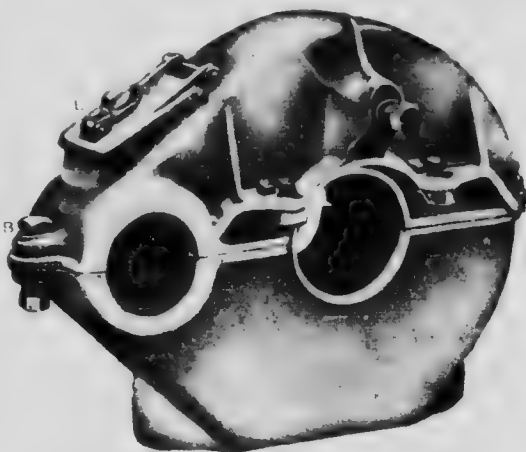


Fig. 646.—Gear Case of Dick, Kerr Tramcar Motor.

is now so universally employed, and parts of which have been shown in several of the preceding illustrations.

Such gearing consists of a single pinion on the armature axle gearing with a toothed wheel on the running axle. The teeth, which are carefully cut to give the proper rolling contact and to minimise sliding friction, are of steel or of wrought iron, though raw-hide pinions have sometimes been used to reduce noise. Owing to the conditions under which they are run these gears are necessarily enclosed in dust-proof gear cases, for otherwise

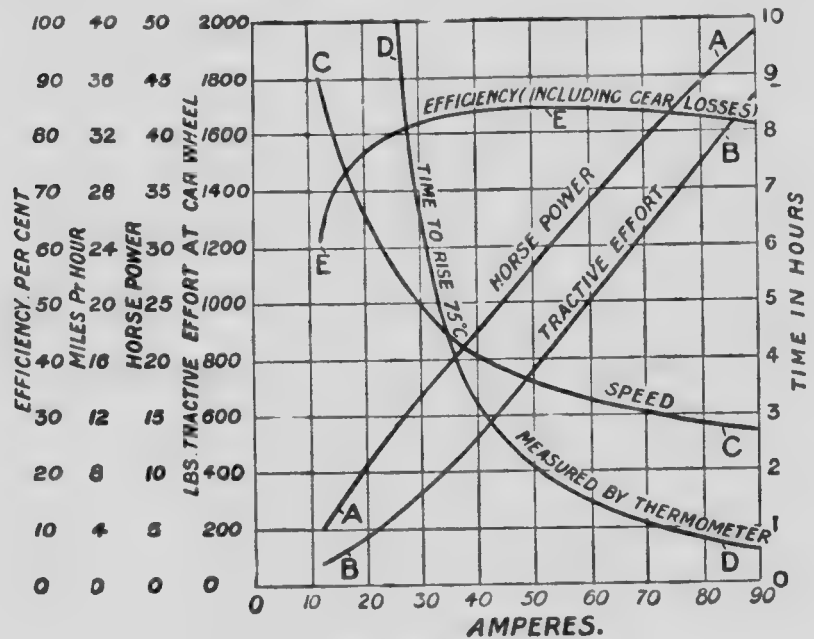


Fig. 647.—Test Curves of Dick, Kerr Tramear Motor.

they would soon be ruined by grit getting between the teeth. Advantage is taken of this necessity to modify the gear case so that it can be used to improve the lubricating arrangements. The details of some such modifications have already been described.

Suspension of Motors.—The methods by which the motors are suspended from the framework of the truck or car are also important. The aim should be to design a suspension with a sufficient amount of elasticity to minimise the effect of shocks, and also to keep the weight of the motor as much as possible from being directly borne by the running axle. A description of the various methods which have been devised to secure these objects would lead us into mechanical problems beyond the limits of this book. Having

called attention to the importance of the subject, the reader is referred to special treatises should he desire to look into the details. Such treatises should also be consulted for the details of the problems involved in the design and construction of motor trucks:

Performance Curves of Tramcar Motors.—It will be convenient slightly to anticipate here the further discussion of the theory of the continuous current motor in the next section of this chapter, by reference to a few curves which give the performance of typical tramcar motors under various conditions of speed, etc.

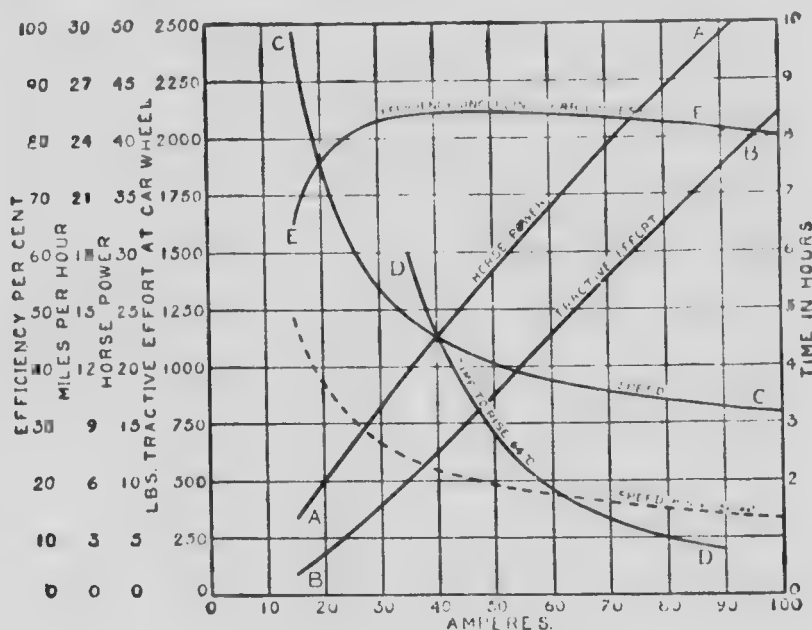


Fig. 648.—Test Curves of Brush Tramcar Motor.

All continuous current traction motors being series-wound machines, it is convenient to exhibit the other quantities in terms of the armature current. Fig. 647 gives the curves for the Dick, Kerr 40 H. P. motor (D.K. 9, Fig. 638) when running on a 500-volt circuit with a gear ratio of 15 to 63 (1 to 4.2) and 33-inch wheels. The curve A A gives the B. H. P. delivered to the car axle for different currents passing through the armature and magnet coils; the loss in the gears being included. Methods of obtaining this curve will be given later, but it may be noted that the curve is not far from being a straight line passing through the origin, thus showing that the B. H. P. is nearly proportional to the current, a somewhat important deduction. Another interesting curve c c gives the speed for different

currents, and it is instructive to note how the current diminishes as the speed rises. The curve BB for "tractive effort," though given in pounds, is really equivalent to the torque, since the force specified in pounds weight is exerted at the circumference of a 33-inch wheel (*cf.* Fig. 573, Vol. I.) The results of temperature experiments are given in curve DD; in DD the various currents are kept on until the temperature of the motor as taken by a thermometer has risen 75 Centigrade degrees above the temperature of the air, and the time taken for the rise is noted. The curve falls away as the currents increase, for then the heat is generated more rapidly.

Perhaps the most interesting curve of the series is the curve EE, which gives the over-all efficiency, including the efficiency (or rather the inefficiency) of the gearing.

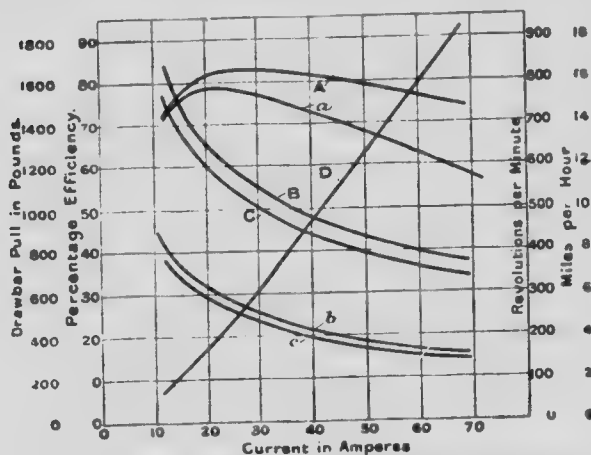


Fig. 642 - Effect of Half-Voltage on Traction Motor Performance.

20 miles per hour falls off very rapidly, the power delivered falling off to below 13 H. P.

As the subject is of great practical importance similar curves are given in Fig. 648 for the Brush traction motor described on pages 625 to 628. A comparison of the two sets of curves will show not only that the corresponding curves in each set are similar in shape, but also that some of the numerical values agree with remarkable closeness. These curves, therefore, may be regarded as exhibiting approximately what may be expected to be the performance of a well-designed 40 to 50 H. P. modern continuous current traction motor as used on trams.

In modern tramcar practice, as will be seen in the section on "controllers," in certain positions of the switch only half voltage, say 250 volts is supplied to the motor. It will, therefore, be interesting to note how the efficiency curves are affected by this diminution of voltage. The results of tests upon another motor under full and half-voltage, are given

ing. The maximum efficiency of about 84 per cent. is reached when the input is about 50 amperes (at 500 volts), and the power delivered to the running axle about 28 H. P., the speed being a little over 13 miles per hour. The efficiency falls off slightly for some distance on either side of this maximum, but above

in Fig. 649, in which the curves *A* and *a* are the efficiency curves obtained under full voltage, 500 volts, and half voltage, 250 volts, respectively. The curves *B* and *C* give the speed, under full voltage, in R. P. M. of the armature and miles per hour of the car respectively, and the curves *b* and *c* give the corresponding data for half-voltage. It is interesting to note how the halving of the voltage reduces the speed to rather less than one half, in accordance with the indications of theory. More important, however, is the much lower over-all efficiency at the lower voltage at which this efficiency never rises above 78 per cent., and with heavy currents

sinks to less than 60 per cent. The gear ratio in this case was 14 to 68 (1 to 4.86), and the draw-bar pull with running wheels 30 inches in diameter is given by the curve *D*.

The dotted curve in Fig. 648 is also a speed curve for half voltage taken with two similar motors in series. It shows a similar reduction in speed to that shown in Fig. 649, but in this case the efficiency curve, which is still more interesting, has not been given.

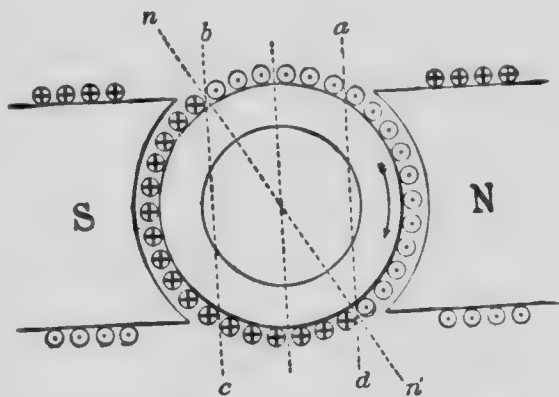


Fig. 65.—Magnetic Reaction of Motor Armature. Case 18.

VI.—FURTHER NOTES ON THE THEORY OF CONTINUOUS CURRENT MOTORS

In Chapter XVI. of Volume I., at pages 601 *et seq.*, some of the fundamental elementary theories underlying the action of the continuous current motor have been dealt with. A few points were left over from that section as being of a somewhat more technical nature, though not very abstruse in themselves. Some of the simpler of these will now be dealt with.

Armature Reactions.—The armature reactions in a continuous current motor will be easily understood after the full discussion on page 502, Vol. I., and page 100, Vol. II., of the corresponding reactions in dynamos. The distribution of current in a bipolar machine when running as a motor is shown in Fig. 650, which corresponds to the dynamo, Fig. 481, Vol. I. The field and the direction of rotation being the same, the current through the armature must be reversed (see pages 500 to 505, Vol. I.), and we have, when the consequent lag (see page 595) has been given to the brushes, a demagnetising belt of six complete turns in the figure between the planes *bc* and *ad*, and a cross-mag-

netising belt of eleven complete turns made up of the remaining conductor. These fields are shown as regards direction inside the armature in Fig. 65, which is the motor analogue of Fig. 482, Vol. I. The result is that the magnetic field is weakened as in a dynamo, and also twisted in the gap, but in the opposite direction to that shown in Figs. 479 and 480 for the case of a dynamo. The trailing horns are now the ones which are weakened, and the leading horns are the ones which are strengthened. But the trailing horns, owing to the lag of the brushes, are now the ones which have to supply the reversing field for commutation. So that finally, as regards commutation, the effect is the same in a motor as in a dynamo—that is, the reversing field is weakened by the armature reactions. This effect has

an important bearing on the problem of regulating the speed, especially on shunt-wound motors.

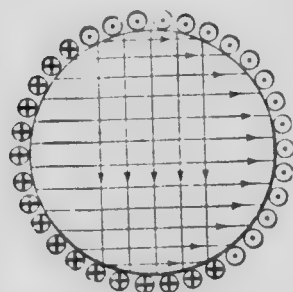


Fig. 65t.—Demagnetising and Cross-magnetising Fields of Motor Armature.

Eddy currents and hysteresis, which tend to twist the field slightly in the direction of rotation, are advantageous in the case of a motor, since they thereby diminish the lag of the brushes and tend to keep up the strength of the reversing flux.

Starting.—The fact, which should never be lost sight of when a motor which is at rest has to be started, is that the stationary armature has electrically a very low ohmic resistance, with no active back E. M. F. to dam back the current. If, therefore, the full voltage which can be safely applied to its brushes when it is running at full speed with its fields excited, be placed on them when it is standing still, in most cases and especially in large motors—an enormous and generally a destructive current would flow through the armature. Some method, therefore, must be adopted for cutting down the current whilst the motor is running up to its speed and developing its back E. M. F. The most convenient plan is the introduction into the circuit of suitable resistances which can be cut out either gradually or step by step as the speed increases and finally dispensed with altogether when full speed has been attained.

Leaving aside, for the present, the question of the economy of the method, we may first inquire as to the best position, electrically speaking for the introduction of these “starting resistances,” and a little consideration shows that this position must depend on the excitation connection of the particular motor. Thus, in a series-wound motor there is only one circuit, and, obviously, any temporary resistance required may be introduced into any convenient part of that circuit. A diagram of the connections of such a motor to the supply circuit is given in Fig. 65, where the two leads pass through a double-pole fuse and the double

pole main switch *s*. One of them is then connected directly to the armature, whilst the other is joined to the movable tongue *a* of a resistance switch, by which the resistances *xxx* can be introduced into or removed from the circuit. Before closing *s*, the tongue *a* should be on stud No. 1, so that all the available resistance is in circuit. As the speed of the motor increases, *a* can be moved round step by step until at full speed it rests on stud No. 12, and the motor alone is in circuit with all the resistances *xxx* cut out. The number of necessary steps for a particular case and the ohmic value of the different resistances must depend on the conditions, but the steps may sometimes be more numerous than are shown in the diagram.

In a shunt-wound motor the case is different. The field-magnet coils can take the full pressure for which the motor is designed, and, moreover, in order to develop the necessary back E. M. F., it is an advantage that they should become fully excited as quickly as possible; this field-magnet circuit of the motor, therefore, can be placed on the supply mains at the first closing of the switch. It is the armature circuit which requires the protecting resistances, and it is into this circuit that they should be introduced. Details of the necessary connections are shown in Fig. 653, where, after passing, as in Fig. 652, through the fuses *F* and the main switch *s*, the circuit is permanently closed through the field coils. Another circuit passes through the armature *A* and some or all of the starting resistance coils *xxx* as long as the tongue *a* is on any stud other than 12. The method of procedure is exactly the same as in the preceding case—namely, to close *s* first, with the movable arm *a* on stud No. 1, and then move *a* slowly from stud 1 to stud 12. Similar precautions must be taken with compound-wound motors, for which the connections will be obvious from the above.

Stopping.—When stopping, an additional point must be borne in mind—namely, that the inductance of the field-magnet coils being large, if their circuit be broken whilst full current is flowing in it, a destructive spark will be caused at the breaking point, and a dangerous shock may be

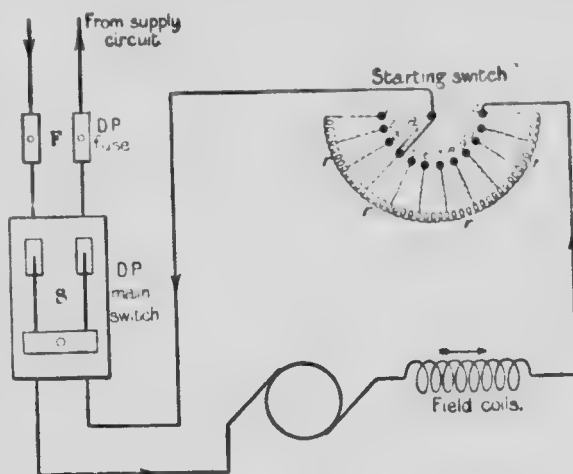


Fig. 652.—Starting Connection for a Series Motor.

experienced owing to the pressure across the break rising inductively to very many times the supply pressure; the insulation also may be broken down by this inductive pressure and the contact surfaces damaged. This effect has already been fully discussed at page 423.

In the case of a series motor (Fig. 652), the main switch *s* must be pulled off when the motor is taking full current and *a* is on 12. Instead *a* must first be moved slowly to 1, and then, when the current has fallen to a small fraction of its maximum value, *s* may be opened.

For a shunt motor the procedure is somewhat different. Here the reluctance of the field magnet is considerably higher, owing to the much

more numerous spirals of the winding. On the other hand, if the motor is connected as in Fig. 653, the field coils are always in a closed circuit, whether the switch *s* be open or closed, and therefore with *a* on any one of the studs, and with the motor running with full current, the switch *s* may be opened. The energy given up inductively by the falling current in the field coils will be discharged through the armature and such of the starting resistances as may

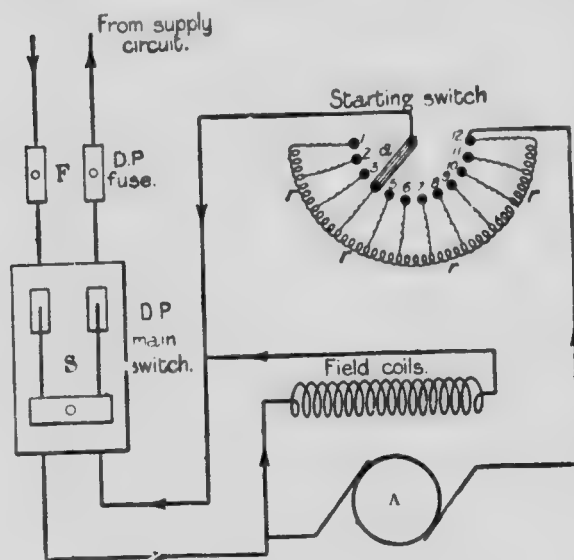


FIG. 653.—Starting Connections for a Shunt Motor.

happen to be in circuit, and there will be comparatively little destructive sparking at *s*. At stopping, therefore, the switch *s* should first be opened, and then, as the motor slows down and stops, the starting switch should be moved back to the first contact (No. 1) so as to be ready for the next start.

The starting resistances and switches for the above purposes may be similar to the regulating shunt resistances already described (see Figs. 178, 179, and 181), with the proviso, however, that the conductors used for resistance must have sufficient cross-section to carry the armature current without destructive heating, though they need not be as heavy as if they had to carry these currents for long periods of time.

Reversing.—In many cases which occur in practice it is desirable

to be able to run the motor either forwards or backwards, for if such reversal of motion at the motor were not possible, complicated mechanical reversing gear would be necessary whenever such reversal is required by the work in hand. One need only cite the case of a tramcar motor or a lift to show how desirable the possibility of reversal at the motor itself is. Moreover, the moving parts of an electric motor are so light for the power dealt with, that in this respect they offer every facility for reversal of motion.

That such reversal is possible is evident from a consideration of the fundamental principles already fully discussed (*see* pages 590 to 595, Vol. I.). All that is necessary is that the direction of the current in the armature *or* in the field-magnet circuit (*but not in both*) should be reversed, when the motor will tend at once to run in the opposite direction.

In early forms of electric motors a preliminary difficulty presented itself here, inasmuch as owing to the lag of the brushes necessary to prevent sparking, if the motion were reversed the brushes would have a lead instead of a lag, and therefore would have to be moved to a new position. Several devices were invented to accomplish this change-over, but the necessity for it has disappeared with improvements in commutating design, the introduction of interpoles, and with the use of carbon brushes, which render it possible to run modern motors sparklessly in either direction with fixed brushes from no load to full load, or even in many cases with a fairly large overload.

It remains, therefore, only to discuss the most suitable changes in the connections required to alter the current flow in the proper manner, and the most convenient way of making these changes, having regard to the fact that between full speed in one direction and full speed in the other the armature will have to slow down and stop, and then increase speed again. The precautions already described as necessary in starting and stopping must, therefore, be borne in mind.

The most convenient way of observing these precautions is to re-introduce the starting resistance as the motor slows down, then make the necessary change in the connections, and remove the resistance as the armature speeds up again. For this series of changes many types of switch



Fig. 654.—Crocker-Wheeler "Cylindrical Reverser."

have been invented. Some of these take the cylindric form, in which successive contact pieces are arranged on the outside of a cylindric bar, the rotation of which by a handle makes the successive changes in proper order by bringing these contact segments into contact with properly connected stationary "fingers." This type of "cylinder reverser" is very widely manufactured, and a simple example, without its cover, as made by the Crocker-Wheeler Company, is shown in Fig. 654. The various cylindric contact segments shown in front rub, as the handle is rotated, against the fingers fixed to the back of the case, and from these fixed contacts the necessary connections are made to the motor.

The action will be best understood by reference to the following diagram. In each case of the two possible methods for attaining the desired result

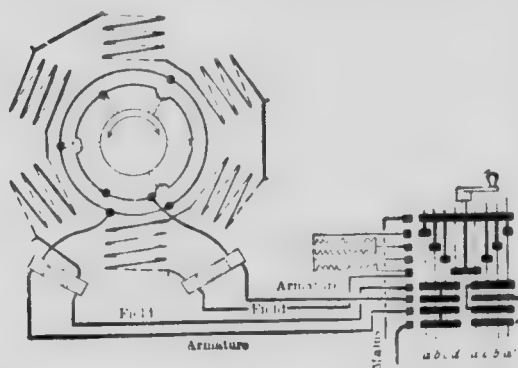


Fig. 655.—Connections for Reversing a Series-Wound Motor.

it is better to reverse the current in the armature circuit rather than in the field-magnet circuit, because (i.) the inductance of the armature being usually much less than that of the field magnets, the sparking at too rapid reversal gives less trouble, and (ii.) as starting resistances are already provided for the armature circuit, these resistances are already connected so as to be conveniently available for

reducing the armature current before reversal, thus again lessening sparking troubles.

Three cases arise in practice according as the motor is a series-, shunt-, or compound-wound motor.* The first-named case, that of a series-wound motor, is depicted diagrammatically in Fig. 655. For the purposes of the diagram, the cylindric part of the reverser is shown "developed," that is laid out flat, at the right-hand side. The movable contacts are represented both in extent and position by the thick horizontal bars, whilst their electrical connections on the cylinder are shown by thick vertical lines. The fixed contacts, nine in number, are shown in a vertical row at the left-hand side of the cylindric contacts, and the fine vertical lines on the cylinder indicate the series of moving contacts which lie on the fixed contacts in any given position of the cylinder. Numbering the fixed contacts from the top downwards, 1 and 9 are joined to the supply mains, 2, 3, 4 and 5 to the ends of the starting resistances, 5 and 6 to the ends

* Figs. 655 to 657 are lent by the Crocker-Wheeler Company.

of the field-magnet coils of the six-pole series-wound motor shown diagrammatically on the left, and 7 and 8 to the brush collector ring, and therefore to the armature. When the first vertical line *a* is placed on the fixed contacts, it will be found that the following circuit is closed: — + main, 1, 2, all starting resistances, 5, field magnets, 7, 6, armature, 8, and back to the — main through 9. Thus the field coils are in series with the armature, with all the starting resistance in circuit. As the switch is turned right-handedly, the vertical lines *b*, *c*, *d* come successively on to the fixed contacts, cutting out step by step, by short-circuiting them, the three starting resistances, and finally leaving the motor running with only field coils and armature in circuit. To reverse, the handle must be turned in the opposite direction, for a mechanical stop prevents a direct transfer from *d* to *d'*. The switch is therefore moved back over *c* and *b* to *a*, reintroducing the starting resistances. At *a* the change is made to *a'* without breaking the field circuit, but on *a'* it will be found that the circuit through the armature is in the opposite direction to what it is on *a*, because of the cross-connection of the armature contacts on the cylinder. The circuit is the same as previously detailed down to stud 6, when it passes to 8 (instead of 7) through the armature to 7, and back to the — main through 9. Moving to *b'*, *c'*, and *d'* in turn, the starting resistance is cut out step by step, and the motor is finally left running in the reverse direction.

The other two cases need not be described so minutely. The connections for the shunt-wound motor are given in Fig. 656. Here the field circuit is joined across the fixed contacts 2 and 9, so that it is energized in every position of the switch. The starting resistances are between 2 and 5, the latter being permanently joined to 6. The armature connections are as in the last case. The procedure is as described above, the difference being that the starting resistances are always, when in circuit at all, in series with the armature, as in Fig. 655, and the method of reversal is as above.

In the compound-wound motor (Fig. 657) the current, after passing from contact 1 to 9 exactly as in the shunt-wound case, reaches the — main with the series-field current, and is therefore independent of the

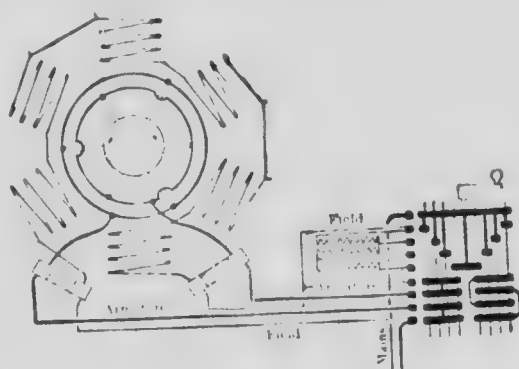


Fig. 656.—Connections for Reversing a Shunt-Wound Motor.

reverser, the shunt current is thus always in the same direction. As before for reversing the motion, the current in the armature only is reversed.

Regulation of Speed.—Many cases arise in practice; we may require the motor to run at constant speed under variable loads, or cases may arise where the speed and the turning torque are both required to vary. In the latter event a fair number of cases must be treated individually and cannot be brought under any general theory, though the considerations applying to the more simple cases will apply *mutatis mutandis* to them.

In regard to the supply of energy to the motor, by far the most usual case at the present time is to have constant P. D. mains available, and we shall therefore first consider the various problems on the assumption that the electric energy is supplied at a constant pressure.

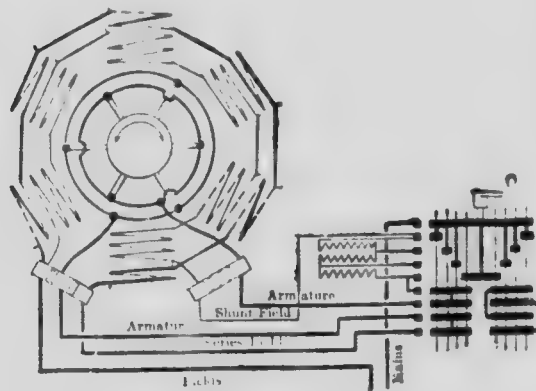


Fig. 657.—Connections for Reversing a Compound-Wound Motor.

Constant Speed.—A glance at Figs. 574 and 575 (Vol. I.) will show that the attainment of constant speed with constant electric pressure on the mains is much more feasible with a shunt-wound than with a series-wound motor. This is also obvious on considering the electrical conditions, for the weak fields of the

series motor with small currents in the armature manifestly require higher speeds to develop the necessary back E. M. F. than does the constant field produced in a shunt motor by a constant P. D. applied to the terminals of the shunt coil.

The drooping of the curve in Fig. 575, however, shows that the regulation is not automatically perfect, although it is assisted by the weakening of the field caused by the armature reactions (see page 100), which would require the motor to run more quickly to give the same back E. M. F. But because of the increase in the lost volts caused by the increased current absorbed as the load increases, the same back E. M. F. is not required, and hence the slackening of the speed, notwithstanding the weakening of the field. It is evident, therefore, that if the speed is to be maintained, the field must be still further weakened. This can be accomplished either by the introduction of resistance into the shunt circuit, or by demagnetising coils in series with the armature, the effect of which will increase as the

load increases, which is exactly what is required. It is difficult, though not impossible, to provide for the automatic introduction of resistance into the shunt circuit controlled by a variation of speed, and therefore the other solution is in practice the more feasible. It is the motor analogue of a compound winding for dynamos, but as the series coils are in this case demagnetising coils, it is often called in practice as *differential winding*, since the resultant field at the poles depends on the difference of the ampere-turns of the shunt and series coils.

Dr. S. P. Thompson has shown that there is a simple relation between the magnet windings and the resistances with which self-regulation will be attained in the case just referred to. Using the same symbols as elsewhere (see pages 514 and 603, Vol. I), and writing r_a and r_m for the resistances of the armature and of the series coil respectively, we have

$$E = n Z N \quad (1)$$

$$\text{and} \quad E = \mathcal{E} - (r_a + r_m) C_a \quad (2)$$

$$\text{but} \quad N = \frac{1 \cdot 26}{\lambda} (s_a C_s - s_m C_m) \quad (3)$$

where s_a and s_m are the number of turns and C_s and C_m the currents in the shunt and series coils respectively. Hence we have from (1) and (3)

$$E = \frac{1 \cdot 26 n Z}{\lambda} (s_a C_s - s_m C_m) \quad (4)$$

and from (2) and (4)

$$n = \left(\frac{\mathcal{E} - (r_a + r_m) C_a}{s_a C_s - s_m C_m} \right) \times \frac{\lambda}{1 \cdot 26 Z} \quad (5)$$

the right-hand side of (5) will be independent of the value of the armature current, and therefore of the load, if

$$\frac{r_a + r_m}{s_a C_s} = \frac{r_m}{s_m C_m} \quad (6)$$

$$\text{but} \quad r_a = \frac{r}{C_a}$$

and (6) becomes

$$\frac{r}{s_a C_s} = \frac{r_a + r_m}{s_m C_m} \quad (7)$$

$$\text{or} \quad \frac{s_m}{s_a} = \frac{r_a + r_m}{r} \quad (8)$$

or, in words, *the number of turns on the series coil should have the same ratio to the number of turns on the shunt coil that the sum of the resistances of the armature and the series coil has to the resistance of the series coil.*

For certain purposes it is advantageous to compound the motor in the usual way—that is, with the series coils assisting the excitation of the shunt coils. This is especially the case when the load is apt to be subject

to sudden and large fluctuations. The effect of the series coil when the load is suddenly increased is to increase the flux, and therefore the back E. M. F., and thus to reduce the momentary excessive rush of current that would otherwise flow.

The danger of weakening the field to maintain the speed lies in the necessity for maintaining a sufficient reversing fringe to prevent sparking at the brushes, and the armature reaction aggravates the difficulty, for, at heavy currents, it weakens the reversing fringe even if the main field be maintained constant. Some of the devices already described (see page 100 to 129), including the use of interpoles for keeping up the reversing flux in dynamos may be advantageously applied to motors, though in most modern continuous current shunt motors the field-magnet flux is sufficiently great at small loads to provide the required margin for commutation when the weakening of the field is only carried sufficiently far to keep the speed constant at heavy loads.

Variable Speed.—The mechanical characteristics of a *series-wound motor* (see Fig. 574, Vol. I.), show that the obtaining of various speeds on either constant P. D. or constant current mains is, at least theoretically, not a difficult matter. The “ ω constant” curve shows that the motor can run at all speeds with the added advantage that at low speeds the torque is at its maximum. For starting under load therefore the theoretical conditions are ideal, and this property has led to the almost universal use of this type of motor for electric tramway work. The practical difficulty is that for these heavy torques at slow speeds the current, as shown in Fig. 573, Vol. I., is also very large, and may be, and is in practice, excessive, so that some method of protecting the motor from injury must be adopted. The usual device is to introduce resistance into the motor circuit which can be cut out as the speed, and, with it, the back E. M. F., rises. The resistance so introduced must be capable of carrying at least the full load current of the motor, and should preferably be able to carry heavier currents. For large motors it will, therefore, be an expensive addition to the equipment, and it is obvious that as it acts by converting the excess energy into wasteful heat, it will also be uneconomical in actual working if the stoppages are numerous or the low speeds persistent.

For traction work, where two, or sometimes more, motors are available, these losses are reduced by the system of series-parallel control, which at low speeds couples the motors in series across the mains, thus converting the excess energy which would damage a single motor if placed on the mains into useful work instead of wasteful heat. As the speed increases the series connections are converted by successive steps into parallel groupings, until at top speeds the whole of the motors are connected in full parallel across the supply mains. Details of the controllers used will be given in the chapter on traction.

If more than one voltage is available, as for instance, in a three-wire supply system, the lower voltages can obviously be used for the lower speeds, and the heat losses involved in the use of added resistances reduced.

The production of variable speeds with *shunt-wound motors* is a more difficult problem. Were it not for commutation troubles it would be comparatively easy to run up the speed of such a motor by weakening the field through introducing resistance into the shunt circuit. In practice, however, this method of speed variation cannot be used to increase the speed more than 30 or 40 per cent. *above the normal*, and then only if the design has been specially adapted for the purpose.

The slow-speed motors described at page 603 were designed with a view to large variations of speed on constant p. d. mains. They had long air gaps, which, while necessitating the expenditure of greater energy in the field coils, helped to diminish the armature cross-magnetisation; for it will be remembered that the reluctance of the magnetic circuit of the cross-magnetising flux consists almost entirely (see Fig. 478, Vol. I.) of the air reluctance of the gap counted twice over, since the reluctance of the iron part of the circuit is comparatively insignificant. At the normal speeds the magnetic flux

is much greater than need be used, so that when, to increase the speed, this flux is weakened, there still remains a sufficient flux for commutation work. Both the above modifications require heavier and more costly fields, but the increased cost is supposed to be justified by the results. In order to minimise the commutation troubles the armature is made large, with numerous bars and small inductance and reactance voltage per section, so that the work of reversal may be done satisfactorily with a weak field.

Advantage has been taken of the properties of the air gap referred to above to use it as a method of control, and machines have even been built with a *variable air gap*. Such a motor brought out in 1905 by the Alliance Electrical Company, Ltd., is shown in Fig. 658 driving a centrifugal pump. It has four poles, only two of which, however, are wound, the other two acting as interpoles, which enable the brushes to be placed in the neutral position. The four cores are movable in directions at right angles to the shaft, and are geared to the hand wheel, so that they can be moved simultaneously inwards or outwards. The theory is simple, and

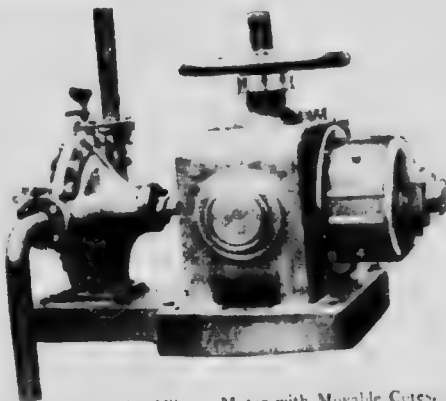


Fig. 658.—The Alliance Motor with Movable Cores.

has been given above with reference to long air gaps. The speed is reduced by moving the poles inwards and increased by moving them outwards. The change of speed can be made gradually from the highest to the lowest speed, and the motor run sparklessly at all speeds with good efficiency, as shown by the curves in Fig. 659, which exhibit the efficiency on actual test at different speeds of a 25-H. P. motor. The lowest curve was taken at half-load, the next at rated load, and the top curve was for a 30 per cent. overload. These curves also show the working range of speed, which is considerable. The standard sizes ranged from $\frac{1}{2}$ H. P. to 110 H. P.

Another method for variation of speed *below the normal* is the employment of additional exciting coils, which push the flux in the iron up to saturation limits, the metal at normal speeds being worked at only moderate fluxes. For further reduction of speed, resistance must be introduced into the armature circuit so as to increase the lost volts and reduce the back E. M. F. required, but the method is uneconomical.

The varying of the speed by control of the field flux may be accomplished in *shunt motors* either (i.) by introducing external resistances in the field-

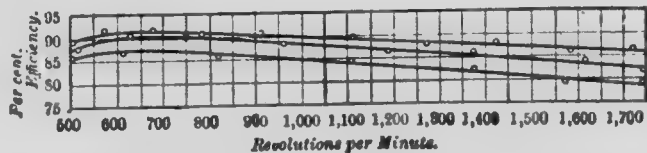


Fig. 659.—Efficiency of a 25 H. P. Motor with Movable Cores.

by winding the exciting coils in multiple or parallel sections, which can be successively cut out of circuit as the field requires to be weakened to increase the speed. In *series motors* the first method is not available; its electrical analogue would be to shunt the field coils with a variable resistance, which drains off part of the exciting current, and so weakens the field. Another method is to wind the magnetising coils in sections in series with one another, bringing out the ends of the sections to terminals at which the coils can be successively short-circuited to keep the field flux more nearly constant as the current increases, thus tending to keep the speed constant. With a magnetically weak armature, this solves some problems which occur in practice.

The control of the speed by introducing resistance into the armature circuit of a shunt-wound machine is, of course, purchased at the cost of efficiency, for whilst the current and the torque remain practically constant, less power is obtained at the lower speeds, the balance being wasted in the resistance coils used. The effect is shown graphically in the curves in Fig. 660, which refer to a 100-volt motor of the Crocker-Wheeler Company of the 2-100 size. The experiments were made with a step-by-step resistance controller with six steps, and the highest speed attained was 184 R. P. M.

The bending over of the curves for the lower speeds before the full graded load of 2 H. P. is reached is very interesting.

As one of the chief difficulties in obtaining a wide range of speed with an electric motor is the difficulty of maintaining sparkless commutation, the *use of interpoles* has, by materially assisting the commutation, done much to increase the range of speed without any other special devices being employed. Several interpole machines have been described above (see pages 583 to 590), and this result of the use of interpoles has been pointed out (see page 591).

Examples of the practical devices employed in reversing the direction of rotation of motors and of apparatus used for maintaining a constant speed, or for obtaining a wide range of variable speeds, will be dealt with in the next section.

Torque.—Series Motors.—On page 603, Vol. I., we have shown that the relation between the electrical and mechanical quantities in a motor is given by the equation—

$$T = \frac{Z N}{2 \pi} C \quad (1)$$

whence if N be constant the torque in a *series-wound* motor is proportional to the current supplied. The condition that N be constant is, of course, only fulfilled in such a motor when the value of the current is such practically as to saturate the field magnets, and usually this is the case with the heavy current rush at starting. When, in such a motor, the current is not sufficient to saturate the fields, as, for instance, when the motor is running light at a high speed, the torque will decrease more rapidly than the current, since c and N diminish together, though not in the same proportion.

Shunt Motors.—The current c in equation (1) is the current through the armature; if we denote this current by C , we have for any motor

$$T = \frac{Z N}{2 \pi} C \quad (2)$$

If we apply this to a shunt-wound motor running on constant pressure mains the P. D. of which is E , we have, employing our usual symbols

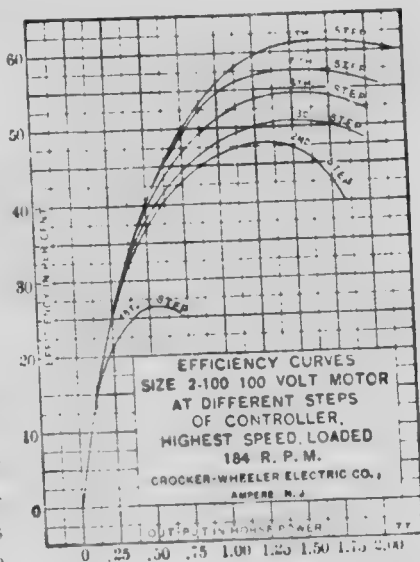


FIG. 66a.—Output and Efficiency at Various Speeds.

$$C_a = \frac{\mathcal{E} - E}{r_a}$$

and since

$$E = n Z N$$

$$T = \frac{(\mathcal{E} - E) E}{2 \pi n r_a} \quad (3)$$

Effect of Supply Voltage.—The last equation shows that, in a general way, a shunt motor which will give a certain torque at a certain speed for a particular value of $\mathcal{E}$ can be re-wound to give the same torque at the same speed for any other value of $\mathcal{E}$. If, for instance, the supply voltage be doubled, it is easy (see page 58) to re-wind the fields to give the same ampere turns at the new voltage, and to re-wind the armature so that r_a and therefore E are doubled. The numerator of (3) will therefore be increased fourfold. The denominator will be similarly increased, since the value r_a increases as z^2 . Thus the value of T remains unchanged for the same value of n . The current through the armature will be cut down one-half, and the same power will therefore be drawn from the mains.

There are, however, limitations. First of all, the law that the resistance varies as z^2 is only true on the supposition that the relative space devoted to copper and insulation remains unchanged. This ceases to be the case when the voltage is pushed up high and the conductors become small; the space devoted to insulation then becomes excessively large, finer conductors have to be used, and the current density in the conductors and their resistance increase rapidly. The former result leads to dangerous heating, whilst the latter more than proportionally increases the value of r_a in (3), and thus the value of T falls.

The higher limit is also affected by the reactance voltage of the commutating sections, which varies roughly as z^2 , and therefore a stronger reversing fringe will be required for satisfactory commutation when the supply voltage is high than when it is low. This may be met, to some extent, by re-designing the commutator with more numerous sections, but there are obvious limits to this remedy.

Though not so often occurring in practice, it may be noted that there are lower limits to the variation of the voltage for which a motor may be re-wound to give the same torque at the same speed, and that these limits also depend upon commutation difficulties. The limit is reached in a given case when the increase of the armature current has reduced the windings on the armature to one turn per section. Further increase of current can only be met by re-designing the commutator with a smaller number of sections, and the further limit in this direction is reached when the current to be reversed at commutation exceeds the capacity of the reversing fringe to effect the reversal.

The effect on the efficiency of re-winding a motor to give the same

torque at a lower speed should not be ignored. As the speed is diminished the efficiency falls at first somewhat slowly and then more rapidly, so that very slow speeds are purchased at a relatively great cost in efficiency, as well as giving proportionately less power. This effect is graphically shown on the curves of Fig. 66r, which refer to tests of a 2 100 Crocker-Wheeler motor. In these curves the horizontal ordinates indicate speed in R. P. M., whilst the vertical ordinates are percentage efficiencies. The motor is designed to give 2 H. P. at 100 R. P. M., or 10 H. P. at 500 R. P. M., and the different curves are for $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, full, and 1 $\frac{1}{4}$ loads of the rated power respectively. They well bear out the above remarks. Thus the "full load" curve shows the efficiency at 550 R. P. M. and 11 H. P. to be nearly 80 per cent., but at 200 R. P. M. and 4 H. P. this efficiency has fallen to 65 per cent., whilst at 50 revolutions less (150 R. P. M.) it is only 55 per cent. Moreover, all the curves fall to zero efficiency to the right of the origin, the meaning of which is that, although the motor would run light (i.e. with no load) at the speed indicated, the moment the load, as indicated by the standard torque, is put on, the motor would stop because of the excessive armature resistance required for that low speed. Thus the motor experimented on would barely take full torque at 100 R. P. M., but would be capable of giving three-quarters or less torque at that speed.

Slow- v. High-Speed Motors.—It has already been pointed out that within reasonable limits electric motors can be built to run at any speed, but that for a given power the lower the speed the larger and more costly the motor. This is because (see page 603, Vol. I.) the power developed is measured by the product of the torque and the angular velocity, and if the latter be diminished, then for a given power a larger mechanical torque must be developed, necessitating a much more substantial machine than is needed to develop the lighter torque required to give the same power at a higher speed. For lightness and cheapness, therefore, high-speed motors are the more advantageous. These are also obviously the best to use for driving directly rotary machines such as fans, centrifugal pumps, polishing spindles, etc., which run at a high speed.

On the other hand, for slow running machinery high-speed motors necessitate the use of reduction gear in the form of spur wheels or pulleys,

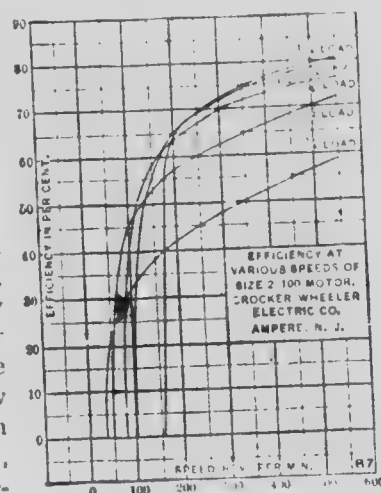


Fig. 66r.—Speed and Efficiency for Various Loads.

or shafting and belts, etc., which not only swallows up part of the saving in initial cost, but also lowers the efficiency of the driving plant, considered up to the point of attachment to the driven machine. Such reduction in gear also takes up space which in some cases can ill be spared. Further, if the motor has to be continually started and stopped—as, for instance, with cranes and hoists, or with a printing press in the process of “making ready”—the energy required to start a high-speed motor is much greater, though the machine is of less weight, than in the case of a slow-speed. The energy required, apart from friction, to set in motion any rotating body is $\frac{1}{2} I \omega^2$, where I is the moment of inertia depending on the mass and size of the body, and ω is the angular velocity, and this quantity is larger for



Fig. 662.—Slow and High Speed Armatures to Develop the Same Power.

a light body running at a high speed than for a similar heavy body running at the relative speed used in electric motors. For instance, the two armatures shown in Fig. 662 belong to two motors built by the Crocker-Wheeler Company to develop the same power (2 B. H. P.), the larger for a multipolar machine at 100 R. P. M., the smaller for a bipolar machine at 1,000 R. P. M. At normal speed the product $\frac{1}{2} I \omega^2$ is 280 foot-pounds for the larger and 900 foot-pounds for the smaller, or 3.2 times as much energy must be expended to start the smaller armature and bring it up to speed as is necessary in the case of the larger one. When, in addition, the smaller machine has reduction gear attached to it, the discrepancy becomes greater.

VII.—CONTINUOUS CURRENT MOTOR WORKING

The applications of continuous current electric motors to various purposes will be dealt with in due course under the different applications of the electric current to the service of man. In this section it is proposed to describe and illustrate modern examples of the actual apparatus used for the starting, reversing, speed-control and safe running of such motors. The examples available are practically innumerable, and, as in other parts

of the book, only a few can be given, which may be taken as typical of numerous others, no slur being cast upon the many excellent examples for which it is impossible to find space.

Necessity for Safety Devices. The precautions necessary in starting and stopping motors detailed in the preceding section are simple to observe, especially if embodied in clear and concisely worded instructions. Nevertheless, unskilled attendants *will* do things the wrong way, if there be a wrong way possible, with unfortunate consequences either to themselves, others, or the fittings and equipment. Moreover, circumstances may arise which may lead to serious consequences without any blame attaching to the attendant in charge of the motor. Suppose, for instance, that the pressure were cut off from the supply mains for a few minutes, a contingency which may occur at any time on "power" mains, the motor would necessarily stop with the switches closed in the running positions. As most motors when once started can be left for long intervals without attention, it may happen that nobody is at hand to put back the starting switch to the starting position. Consequently, when the supply mains are again energised, a destructive current will flow through the armature before the motor can get up speed. Then, again, those who are using the power may put on an excessive load, causing the motor to slow down, and draw from the mains an excessive current. It may be said that as there are fuses in circuit these should "blow" and cut out the motor, but a current not sufficient to blow the fuse may damage the motor if kept on for a long time. For both cases, "automatic" switches should be devised, if possible, so that either for "no-volts" (the first case), or for an "overload" (the second case), the switch would automatically cut the motor out of circuit, and make it impossible for it to be started again without the proper procedure being observed.

In practice, in addition to providing for the contingencies just referred to, it is frequently convenient to be able to vary the speed of the motor to suit the particular work required at the moment, and even at times to reverse the direction in which the motor runs. There are, of course, mechanical methods of changing speed and reversing the direction of rotation, and such methods have to be adopted in a factory where all the power is obtained by mechanical transmission from a single prime mover, such as a steam or gas engine. It is, however, one of the advantages of electric motors that not only can the power be brought to them readily by flexible copper conductors, but that, further, certain types can run in either direction and have, within limits, ranges of speed which are very convenient for many industrial operations.

To take full advantage of this flexibility in the use of electric motors, it is necessary to design the switching apparatus with great care, and with a full knowledge of the conditions of the work for which the motor is required.

So important has this branch of electrical manufacture become, that in addition to the large firms having special departments for it, quite a number of firms have made it a speciality, and practically devote themselves entirely to it. For our purposes, although there may be some overlapping, it will be convenient to deal with the apparatus as grouped into various classes according to the particular purpose immediately in view, and also at times, according to the leading feature of the design.

Starting Switches.—The chief object of a starting switch is to supply a ready and convenient means with all the necessary apparatus, not only to "start" a continuous current motor of a specified output, but also to provide the safety devices which will operate either (i.) if an attempt be made to start the motor too quickly, or (ii.) if the supply of electric energy fails, or (iii.) if the motor be overloaded. Such switches as we are concerned with here are arranged for *shunt-wound* motors, and they may be classified as shown in the following paragraphs according to certain general features.

Face-Plate Starters.—In these, which are almost universally employed for small motors, the apparatus is mounted upon a flat plate, usually made of slate or marble, and the necessary contacts for making connection to the different sections of the rheostat or resistance are frequently, but not always, arranged consecutively on a circular arc. The other apparatus to be mounted on the plate will appear in the sequel.

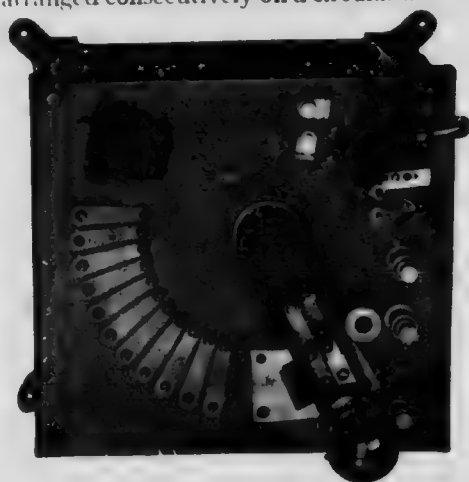


Fig. 663.—B. T.-H. Face-Plate Starter.

A starting switch of this type, which is perhaps the most generally used, for a shunt-wound motor, made by the British Thomson-Houston Company, Ltd., is shown in Fig. 663, and may be taken as typical of the simpler switches having a no-voltage and overload release. In this type the multiple contacts for dealing with the resistance are arranged, as just explained, in a plane on a slab or face plate and the

necessary contacts are made by sliders or wipers moving over the plane surface, these sliders or wipers being most frequently, but not always, near the extremity of a radius lever or arm. In the British Thomson-Houston starter the switch arm, magnets, and contacts are mounted on an enamelled slate panel, and the action of the switch will be

readily followed by reference to Fig. 664, in which the various details of the apparatus on the front of the panel in Fig. 663 are shown diagrammatically in the same relative positions, with the exception that the arm of the switch appears on the "running" instead of on the "off" stud. The resistances between the contact studs (see Fig. 653, *note*) are mounted behind the slate in the space between it and the frame, by which it can be fixed in any convenient position.

Referring to Fig. 664, the current coming from the supply circuit passes first through the fuses *F* and the main switch *S*, both double-pole. The $+$ lead is carried directly from the main switch to the motor and attached to the $+$ terminal, which on this diagram has also one end of the field-magnet (shunt) coil attached to it. The $-$ ends of the field and armature circuits, and the $-$ lead are connected to the switch panel as shown. With the switch open, as in Fig. 663, it will be found that, *s* being closed, there is no circuit through the machine, as the $-$ line pole is connected to the movable arm *B*, which is on the idle strip *r*. When the arm *B*, moving forward,



Fig. 664.—Connections of B. T. H. No Voltage and Overload Release Switch.

reaches the strip *s*, two circuits are closed—namely, (i.) the field-magnet circuit through the field coils, the terminal *F*, the no-voltage magnet *N*, the arm *B*, and the overload magnet *O*, to the terminal *M* and the $-$ pole, and (ii.) the armature circuit through the armature, the terminal *A*, all the resistances *r r*, to the arm *B*, the overload magnet *O*, the terminal *M*, and the $-$ pole. The motor then starts, and as its speed increases, *B* is moved slowly over the remaining contacts until it reaches the last. Then all the extra resistances will be cut out of the armature circuit, and simultaneously a soft iron plate attached to *B* will be attracted and held firmly, for the full field current is flowing through the magnet coils, by the poles of the electro-magnet *N* against the pull of a spring. The spring referred to is coiled up on the hub of the arm, so that the clockwise motion of the arm coils it up still further. The combined currents, it will be noted, flow through the coils of the magnet *O*, which, however, has not sufficient

coils to give with the normal working currents the necessary ampere-turns to attract its armature *c*.

The automatic action of the switch in each of the cases under consideration is very simple. If, when the switch is closed and the motor running, the volts are taken off the supply circuit, the no-voltage magnet will lose current and be unable to hold its armature, which will be pulled off by the coiled spring, which will also pull the arm *B* rapidly over to strip 1. Thus the motor will be disconnected entirely from the — line, but its field magnet circuit will be left closed through the armature, thus avoiding destructive inductive flash. When the supply circuit, therefore, is again energised, the motor will have to be started in the usual way.

Suppose, next, that the motor when running is overloaded, and slow down, its back E. M. F. will be diminished, and consequently it will take more than its normal current. This excessive current will flow through the electro-magnet *O*, and increase the ampere-turns sufficiently to attract *c* and bring the bridge *b* against the contacts immediately above it. These

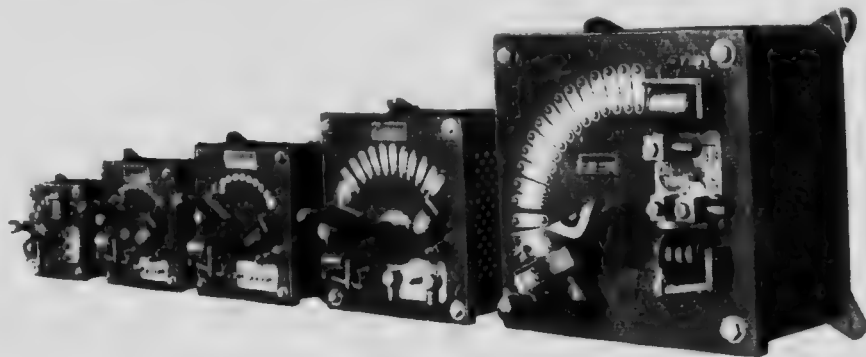


Fig. 665.—A Line of Westinghouse C. C. Face-Plate Starters

contacts being connected directly to the two terminals of the magnet *N*, the coils of this magnet will be short-circuited, and will lose their current, releasing the armature, and cutting the motor out of circuit, as in the preceding case. By an adjustment at the plate *c*, the armature of the magnet *O* which is held "off" by its own weight, can be set at any convenient angle. It is usually adjusted to move upwards with an overload current of 50 per cent. in the magnet coils. When the arm *B* flies back the magnet *O* loses its current and *c* drops down by its own weight on to the supporting rest, thus leaving the switch quite ready for a fresh start.

With respect to mechanical details, it may be pointed out that the switch shown in Fig. 663 is made with *renewable contacts*, in other words,

if the contact pieces should wear thin by friction, or sparking, or both, they can be detached, and new contact pieces inserted. A cheaper form of the switch is made, in which simple contact buttons take the place of these renewable contact pieces. Another point is that there are two contact fingers on the switch arm. The forward one is thus in contact with the next fixed contact piece before the backward one leaves the preceding contact piece. The circuit, therefore, when once made, is not broken on the contact pieces. Other methods of dealing with the sparking difficulty will be referred to as we proceed.

As a further example of face-plate starter, Fig. 665 illustrates a line of Westinghouse starters for motors ranging from $\frac{1}{4}$ to 75 B. H. P. Further detailed description is unnecessary, but the reader should carefully compare the arrangements on each of these starters of the standard type already described, with its arrangement on the others, and on the B. T.-H. starter in Fig. 663. As to details, it will be noticed that the two larger starters have renewable contacts for the rheostat connections, and that the three smaller have permanent stud connections only. A feature of these starters is that a *diagram of connections* is permanently attached to the front of the starter and is, therefore, always available, so that it should not be possible to make a mistake in joining up the starter to the motor and the mains.

The above starters will serve as the type of many similar starters, all using the same general principles of construction, but differing in the arrangement of the parts of the apparatus and in mechanical details. These points are, of course, of great importance, but to describe every variation fully would be tedious. As examples of other face-plate starters will be given presently in connection with other points there is less need for additional separate descriptions.

Passing, then, from individual starters of this type, Fig. 666 illustrates a complete outfit such as has been indicated as necessary in Fig. 664 for the installation of a c. c. motor. It represents a "motor-control panel" as designed and manufactured by Messrs. Brook, Hirst and Co., Ltd., of

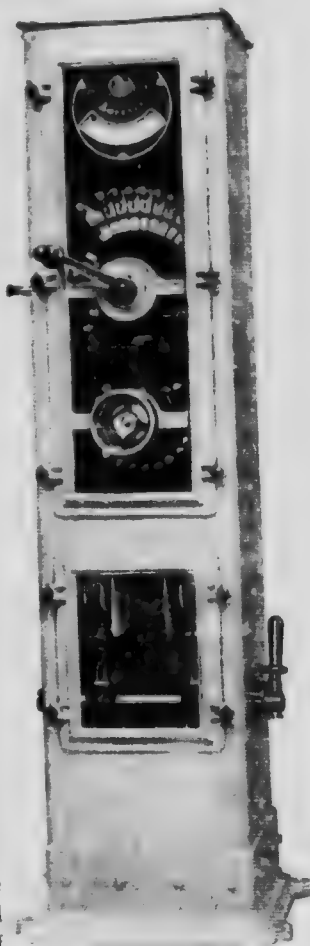


Fig. 666. —Control Panel of Messrs. Brook, Hirst & Co., Limited

starter. The whole of the apparatus is contained in a metal cabinet or case, which can be made quite dust-tight, and is so designed that the switches can be manipulated from the outside without opening the doors.

The bottom compartment contains the main switch (see Fig. 100), which, in this case, is a circuit breaker, so interlocked with the starter that it can only be put "on" when the starter is "off." In the compartment there is an ammeter to measure the current used, the scale of the ammeter being visible through the glass panel when the door is closed. The top compartment also contains the starter, which is of the general type described above, but which is also interlocked with the main circuit breaker in such a way that it cannot be put "on" until the circuit breaker is fully closed and its handle free. It is noticed that the contact plates for the series starting resistance are fairly numerous, and that there is arranged on an external cone a series of additional contacts, so placed that they cover the dividing gaps in the other, so that they take up the space which may occur as the switch arm is moved round. These external contacts consist of carbon buttons or rollers, which cannot be damaged by the spark. A "no-volt" shunt coil holds the switch arm in the "on" position while current is "on," but the "overload" solenoid is connected to a "no-volt" coil on the main circuit breaker by means of a wire, which, when raised by an excessive current, will draw the switch arm to the terminals of this "no-volt" coil and trip the circuit.

Below the starter there is a regulating switch for varying the speed of the motor, to which further reference will be made later.

The switches can all be manipulated from outside the cabinet: the D. P. main switch, or circuit breaker, by a handle on the right-hand side, the starter by a handle in front, which engages with the axle of the movable arm when the door is closed, and the speed-regulating switch by a hand wheel below the starting handle. It is possible to design the fittings of these doors so that they can be opened whilst the circuits are alive, the interlocking device being placed on the axle of the external handle of the starter.

Compression Starters. In the starters so far described the wire resistances, subdivided as found necessary, and with appropriate contact plates at the dividing points, have been used to vary the electrical conditions. Such resistances may be used in certain circumstances and for large motors, costly; they require space, and they are liable to get out of order. Attempts have therefore been made to vary the conditions in other ways. A successful starter, in which no wire rheostats are used is shown in Fig. 66; it acts as a "compression-type" starter, as designed by Messrs. *Electric & Mechanical Engineering Co., Limited*. The resistance

material used is graphite, which is one of the allotropic forms of carbon and has a specific resistance (Table IV., page 2, Vol. I.) some ten times that of

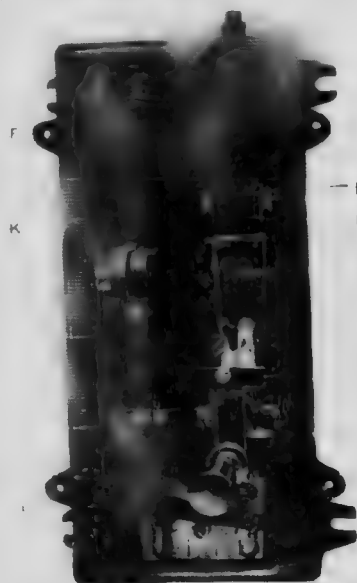


Fig. 667.—Ferranti Compression-Type Starter.

carbon in the tubes used for arc lights or glow lamps. The material is compressed into discs of suitable diameter and thickness, and the discs are assembled like a roll of paper in the steel tube K (Fig. 667), the interior of the tube being lined with a very insulating material having the same coefficient of expansion as the tube itself. If a current is passed through the discs from one end of the tube to the other, the resistance of the discs, as the contact resistance between disc and disc, is the value of which will

depend upon the tightness with which the discs are packed, and which will diminish through a wide range as pressure is applied.

In the starter, shown open in Fig. 667, which looks very like an ordinary circuit breaker, the resistance material in the tube takes the place, electrically, of the resistance r in Fig. 664. The connections, which exhibit some small variations from the usual ones, though the principles involved are the same, are shown diagrammatically in Fig. 668. When the handle, and with it the arm A, is moved to close the switch, it first closes the main switch by a simple link gear directly connected to the handle. It also bridges the arcs B and C (Fig. 668), which are used in the most recent patterns, thus putting the armature across the mains in simple series with the overload coil, the blow-out coil, the resistance discs in the tube K, whilst the field magnets are, as usual, put across the mains in series with the "no-volt" and overload coils.

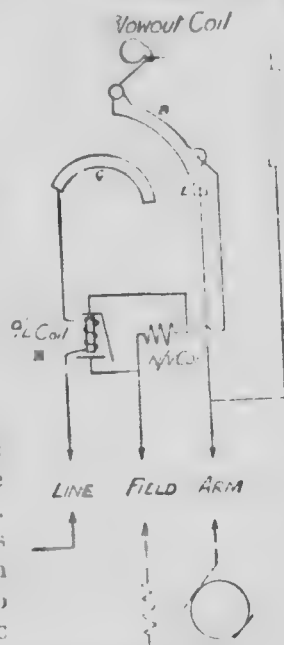


Fig. 668.—Circuit of Ferranti Starter.

As the motion continues the carbon discs in the tube are compressed more and more by the action of the lever B (Fig. 667), which is mechanically coupled to A, and by means of a rod H presses upwards a plate situated inside the cylinder at the lower end F. Simultaneously the rod C is pulled downwards and brings with it another plate inside the cylinder at the top end F₁. Between these two plates the discs are compressed and their resistance gradually and continuously reduced until the switch is closed home when they are short-circuited by the radial contact arm slipping from the arc B to the stud E (Fig. 668). The switch arm is held on by the "no-volt" coil L (Fig. 667), whose poles P hold the armature O on the movable arm of the switch. The armature will be released and the switch tripped if L loses current either by the failure of the supply or by the action of the overload coil, the attraction of whose armature (Fig. 668) short-circuits the "no-volt" coil in the usual way. With the first motion backwards the

radial contact arm slips from E to B (Fig. 668), putting back into circuit the resistance D and the blow-out coil, which can be seen between the contact jaws M in Fig. 667, and when the switch is closed directly opposite the contact tongues X. The overload coil is at J, just above the no-volt coil L.

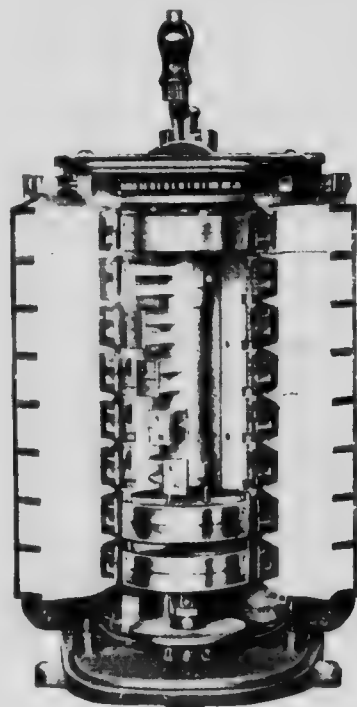


Fig. 669.—A. B. T. H. Cylindric Starter.

Drum or Cylindric Starters.—This type of starter, which can be used for heavier currents than those just described, has been referred to and illustrated in connection with the "reversing" of motors in the section on theory (see pp. 644 to 648 and Figs. 654 to 657). When it is not required to provide for the reversing of the motor two of the armature contact pieces shown in Fig. 654 may be omitted. A starter of this type is shown in Fig. 669, which exhibits the details of a starter made by the British Thomson-Houston Company and should be compared with Fig. 654. An additional starting segment is provided in Fig. 669, so that the starting resistance to be thrown into the armature circuit is divided into four sections

instead of into three, as in the previous case. Each cylinder segment and each finger, is also divided into two parts, which facilitates the repair and renewal of the rubbing surfaces. The starter is shown with the covers

thrown back, and it will be noticed that these covers carry dividing partitions which, when the cover is closed, are interposed between the working contacts; these partitions are designed to prevent sparking between neighbouring contacts when the circuits are being broken. The starter shown in Fig. 669 is rated for intermittent working with motors up to 100 H. P. on 250 volts or 200 H. P. on 440 to 550 volts.

When the conditions of current and voltage render it necessary a magnetic blow-out is added. The principle of this device has been explained in Vol. I. (see page 271). Its application is shown in Fig. 670, which represents a B.T.H. starter and speed controller combined. The magnetising coil for the blow-out magnetic circuit is carried on a

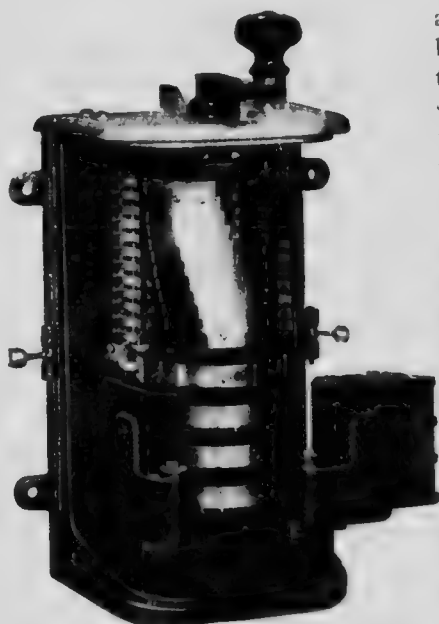


Fig. 670.—A B. T. H. Motor Starter and Speed Controller, with Magnetic Blow-Out.

bracket attached to the right-hand hinge, the hinge being shown in the "open" position. When the hinge is closed and the coil energised, the magnetic flux will be directed between the heavy contact segments on the barrel and at right angles to the current of any arc which might be set up between those segments or the fingers with which they may be breaking contact. The conditions of Fig. 235 (page 270) of Vol. I. are therefore satisfied, and the arc would be magnetically blown out. The speed-regulating section of this controller will be referred to later (see page 680).

The conditions of motor service are so varied that it is impossible to refer to all the varieties of starters which have been designed to deal with them, and some will be more

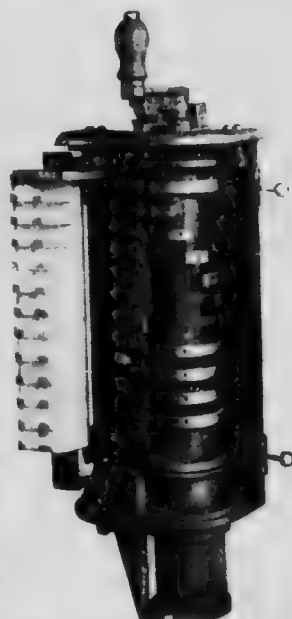


Fig. 671.—A Spring Return Starter for Cranes and Hoists.

appropriately described in connection with the particular applications. A brief reference may, however, be made to the starters intended for those applications, in which the motor only runs intermittently and in which, therefore, the starter is required to be so designed that it never leaves the motor in circuit. This is the condition obtaining, for instance, with cranes, hoists, lifts, etc. A drum-type B. T.-H. starter for these cases is shown in Fig. 671. It is an ordinary reversing starter, with a powerful spring added, which is coiled up as the handle is turned. As soon as the operator's hand is removed from the handle, this spring at once returns the starter to the "off" position. In cases of this kind the starter is also conveniently used as a speed controller, for which the starting resistances are available (but, *see* page 652).

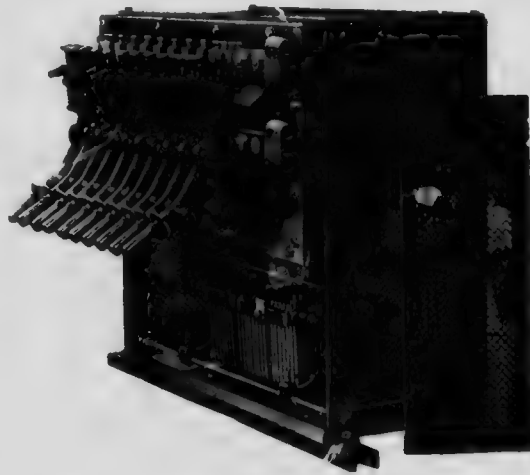


Fig. 672.—Westinghouse Multiple Switch Motor Starter.

The above cylindrical starters do not contain a "no-volt" or an overload release, which, if required, must be provided by a separate circuit breaker. These devices can, however, be fitted to cylindrical controllers, and a controller so fitted will be described later (*see* page 679).

Multiple-Switch Starters.

For large motors at moderate voltages for which heavy currents have to be handled the sliding contacts involve sparking difficulties, which some designers overcome by modifying the design and providing a separate switch in the place of each contact stud of the ordinary starter. The modification is an expensive one, but is held to be justified by the results, and incidentally it lends itself to the adoption of a simple "fool-proof" device.

A "multiple-switch starter," of this type, as manufactured by the British Westinghouse Company, is shown in Fig. 672, which shows the switch with some of the resistance covers removed. The circuit breakers are mounted on a face plate, which in its turn is mounted on the front of an iron-frame receptacle which contains the necessary resistances. The number and size of the circuit breakers used depends on the size and voltage of the motor which is to be operated.

The switches, ten in number, it will be observed, are ranged side

by side on the face plate. This enables them to be mechanically interlocked, like the levers in a railway signalman's cabin so that it is impossible to close them in any but the correct order and one by one. As each switch has to be closed separately a longer interval of time must elapse between the closing of successive switches than is necessary with the usual sliding contacts, thus giving the motor a chance of getting under way. There are the usual no-volt and overload release coils, energised and acting in the usual way; but, of course, only one of each for the whole starter; in other words, the circuit breakers are not individually automatic. The no-volt coil, however, instead of being placed in the shunt circuit of the motor, is placed in series with a resistance in a separate shunt circuit across the mains, and a separate discharge path is provided for the shunt fixed winding. The overload release coil is only provided for starters up to a rating of 100 H. P. on 100 volts and 150 H. P. on 200 to 500 volts. For larger motors, if an overload release is required, it is provided by a separate single-pole overload release circuit breaker mounted on the face plate of the starter, but connected in the opposite line to the starter.

Fool-Proof Starters.—There is one contingency for which the above switches do not provide, and although it is true that this contingency can only arise through gross carelessness, it is thought by some to be sufficiently probable to justify a special safeguard. It is this—suppose the attendant, having closed the main switch S (Fig. 664), moves the starting lever B as *rapidly* as possible, and forcibly holds it over instead of, as directed, moving it *slowly* and waiting for the motor to speed up, there will at once be a dangerous rush of current through the armature, and although the "overload" coil will come into action and short-circuit the no-voltage magnet X, this short-circuiting will be of no avail, since the arm A is being *held over* by the operator. The consequences, which will probably be disastrous to the motor, and were intended to be guarded against, will therefore happen.

Such stupidity can be made harmless by the use of "*circuit breakers*" in the main circuit or the armature circuit. The principle underlying such apparatus has been referred to in the preceding pages (see pages 560 and 571) when dealing with oil switches, and a whole chapter could be written on its various applications. The usual device is to have the lever of the switch held in position against the action of a strained spring or gravity by some kind of a trigger arrangement; the armature or moving core of the overload magnet is then arranged so that when the excessive current passes, it knocks off the control, allowing the strained spring or gravity to operate and force the lever arm out of the contacts. As a considerable current is thus suddenly broken, the final break is usually taken on carbon contacts since the destructive inductive flash would readily fuse ordinary metallic contact pieces.

The installation of expensive circuit breakers is, however, to be deprecated if the end can be attained in less expensive and more direct ways, and there are now obtainable various forms of starters designed to be "fool-proof," or such that they make no demands on the intelligence or even on the memory of the user. These can be grouped conveniently according to the chief device relied upon.

Slow-Motion Face-Plate Starters.—It is obvious that in the starters already described, which all depend upon the movement of a radius arm or lever, the object sought will be attained if the mechanical construction is such that this arm can only be moved quite slowly. This can be accomplished,

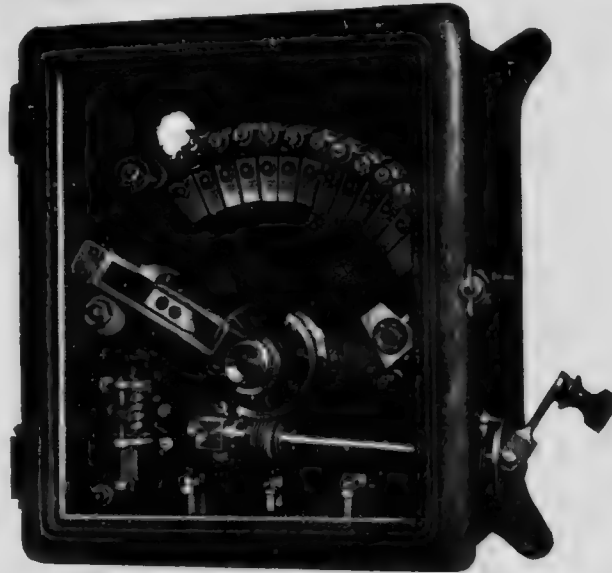


Fig. 673.—Brook, Hirst & Co.'s Slow-Motion Starter.

first, by enclosing the arm itself in a locked case, and, secondly, by imparting motion to it by means of a worm wheel and geared pinion, or segment of a pinion, or by some other mechanical device which ensures that the arm can only be moved slowly. The ratio between the rate of movement of two axles geared with worm and

pinion can be made as reasonably great as may be deemed necessary.

The device of a worm gearing into a toothed wheel to obtain the desired slow motion is illustrated very distinctly in Fig. 673, which shows a standard starter manufactured by Messrs. Brook, Hirst and Co., Ltd., and similar to the one described on page 661 (see Fig. 666). The details of the slow motion are so clearly shown that further description is scarcely necessary. The general plan of the starter will be understood from what has already been said, but the details of the overload release solenoid, and of the no-volt release magnet, should be noted, and also that the rubbing contact for the segments of the resistance studs carries the current by a bridge piece in the lever directly over to a special contact surface at the centre, thus avoiding any flow of current through axles or loose contact

joints. This device is used by other manufacturers (e.g. see Fig. 675). It should further be noted that the door of the box is left quite clear.

A different mechanical arrangement for obtaining the slow motion is shown worked out in Figs. 674 and 675, which give two views, one with the case open and the other with the case closed, of a standard "motor-control pillar," as made by the British Westinghouse Electric and Manufacturing Company. In the lower part of the case (Fig. 675) there is mounted one of the standard step-by-step starters of the face-plate type made by the company, and

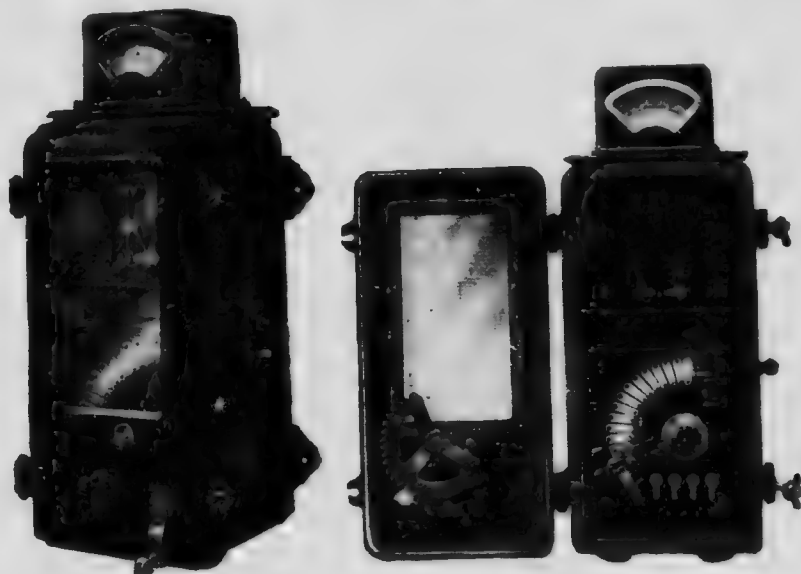


Fig. 674. - Close

Fig. 675. - Open

Westinghouse Motor Step-by-Step Starting Panel.

above it the main switch and fuses. An ammeter is placed on the top of the pillar to measure the current being used. What, however, we are most concerned with, at the moment, is the segmental piece of a notched or toothed wheel, shown mounted on the back of the door in Fig. 675. This is to be operated by a single tooth mounted on the axle of the handle A seen in Fig. 674. Even if this handle be turned quite rapidly, it will be obvious that the segmental wheel can only be moved by one tooth at a time for each revolution of the handle. When the door is closed, the hub of the wheel clutches on to the hub of the radius-arm or the starter, which will therefore be moved step by step at a rate depending upon the velocity of rotation of the handle, thus giving the motor time

to start up whilst the fingers of the switch are traversing the contacts of the face plate. In other respects, the operation of the starter is similar to those described above. The door (Fig. 674) is usually secured with swing bolts and wing nuts, but can be fitted with lock and key if deemed necessary. The main switch operating handle can be seen on the right-hand side of the pillar in Fig. 674. The small handle in the middle of the front cover operates the ratchet seen in Fig. 675, and enables the starter to be locked on any segment whilst the handle is being operated. The ratchet ceases to hold when the electro-magnetic clutch operates in the "full on" position.

Free-Handle Devices.—Another method for guarding against the possible stupidity of some of the operators of motor starters is the use of a free handle. The principle is that the moving lever is in two parts temporarily clutched together, one only of which is controlled by the operator. The clutching is so devised that if the position guarded against is in danger of being set up, the clutch will be released and the independent lever by its motion will relieve the situation.

The principle will be best understood by a concrete example, and for this purpose we cannot do better than describe the "free-handle motor starter" of Messrs. Ferranti, Ltd., shown in Fig. 676. The figure shows the two portions of the handle lever separated, the part under the control of the operator being at the limiting "on" position, and the part independent of his control at the limiting "off" position. It is this latter part which is the real contact lever. In addition to the whole lever being split, the no-volt coil is carried on a bracket on the operator's section instead of being fixed to the face plate in its usual position. When the two levers are together in the starting position, the free lever is clutched mechanically on to the operators' lever, until the combined levers are moved sufficiently forward for contact to be made with the first resistance stud. As

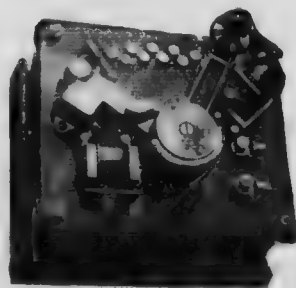


Fig. 676.—Ferranti Free-Handle Motor Starter.

soon as current flows, the coil on the operator's lever is energised, the mechanical clutch is thrown out, and for the rest of the movement the free lever is clutched only by the magnetism of the no-volt magnet. In the event of the current becoming excessive, the overload magnet acts in the usual way, the no-volt coil loses its current, and the free lever is immediately released, and flies back to the "off" position, thus cutting the motor out of circuit. When in the "full-on" position, the operator's lever is held by a mechanical catch, the free-lever being still clutched to it by the no-volt magnet. The switch is, therefore, ready to act in the usual way, and can be left to itself.

Dash-Pot Retardation.—The principle of the dash-pot has also been employed to obtain the necessary safeguard against the idiosyncrasies of the operator and to ensure that the quickness of the operation shall be beyond his control. In this connection a brief reference may be made to the so-called "Direkton" starter, manufactured by Engineering Instruments, Ltd., of Darlington, and illustrated in Fig. 677. The starter is also interesting from the fact that the sliding contacts for the sections of the resistance, as seen at the right-hand side of the operating handle, are arranged vertically in a straight line. The operator's instructions are simplicity itself, namely to "close the switch" and press it home. In doing so, he compresses which in its recoil works against the fluid dash-pot. The piston can then only give way slowly to the pressure of the spring, and in doing so carries with it the sliding contacts which step by step remove the resistance from the armature circuit. The no-volt coil faces the closed jaws of the switch, and the overload solenoid ready to short-circuit the two contacts above it can be seen at the side. Both these are in circuit from the moment of closing the switch, and will therefore operate if anything wrong should happen whilst the resistances are being removed. For instance, if the dash-pot were not retarding the movement of the wipers sufficiently, the overload coil would act and the switch fly open unless, perchance, the operator was still firmly holding it on, a not unlikely circumstance. The terminals L, F and A are connected to line, field-magnet coil, and armature respectively, the other line being taken direct to the other armature brush as in Fig. 664.



Fig. 677—"Direkton" Starter.

Automatic Starters.—The apparatus so far described, notwithstanding its automatic safety devices, requires that the operator shall himself personally attend to the operating handle of the starter or controller, and this not only introduces the personal element, the idiosyncrasies of which are guarded against in "fool-proof" apparatus, but also requires the operator to be present at a particular place to perform the operation.

This last requirement may lead to inconvenience, and in some cases to an increased cost of operation when compared with an arrangement in which the starters and controllers can all be operated electrically from a central point, as are the switches in the case of remote-control boards, described at pages 547 to 567. It is obvious that the same method can be applied to the apparatus now under

consideration if only the details be worked out with sufficient mechanical and electrical skill, and with a full knowledge of the conditions of service. The problem is to devise apparatus on an engineering scale, using the principle of the relay, invented by Wheatstone, and which is described at page 392 of Vol. I. The automatic oil switches described on pages 567 to 574 are an illustration of the engineering application of this principle.

A very complete system of such remote control for the starting, stopping, speeding, and reversing of electric motors has been worked out by the experienced engineers of the British Thomson-Houston Company, Ltd.,

and a description of some of the apparatus used will enable the reader to grasp the main conditions of the problems solved.

The non-reversing starting rheostat of this system, applicable to continuous current motors up to 15 B. H. P., is shown in Fig. 678. The relay part of the apparatus is known as a "contactor," and is mounted on the right hand side of the face plate. It is a relay, the line or primary circuit of which can be closed at any convenient point, causing a comparatively small current to flow through the solenoid, which can be clearly distinguished in the figure. When the "line" circuit is closed this solenoid exerts a powerful pull on the arm

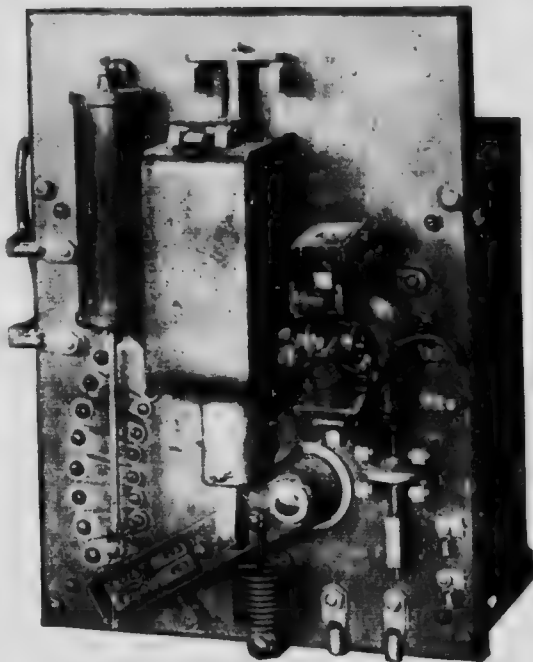


Fig. 678.—B. T.-H. Automatic Starter for C. C. Motors up to 15 B. H. P.

of the main switch, which it closes against the action of strong "pull-off" springs. A small buffer spring, seen below at the side and acting through a link motion, mitigates the shock of the final impact of the contacts. The main circuit being thus closed, a shunt current flows through the coils of the long ironclad solenoid on the middle of the board, which acts as a long pull electro-magnet. Its plunger is linked on to the lever arm of a face-plate starter, and by the motion of the plunger the arm is made to traverse slowly the various contacts of the starter, producing the usual results. The action is slow,

firstly, because the pull of the plunger is counteracted to some extent by the coiled spring, and secondly because of the action of the dash-pot, the piston of which is being pushed upward against fluid pressure by the rod which is seen connected to the end of the starter arm. The rate at which the movement of the arm is allowed to take place can be accurately adjusted beforehand, the usual period in this pattern for the completion of the operation being fifteen seconds from the closing of the "line" circuit.

When the contactor is closed, since the current in the solenoid is not retained, it is held closed by a mechanical trigger device, which can be tripped by an overload current. In this and also in the "no-volt" case the solenoid loses its current and the spring brings the starter arm to the "off" position. The action of the contactor as a circuit-breaker is

quick and positive, and as it is fitted with a powerful magnetic blow-out (see page 665), it can open the circuit on heavy overloads without appreciable arcing or fusing of the contacts. The whole of the apparatus is so designed as to enable replacements of worn or damaged parts to be made quickly and easily.

It is obvious that in its turn the closing of the "line" circuit can be automatically effected by floats, pressure governors, or other mechanical devices suitable for particular conditions of service, and also that this closing can be made at various points for one and the same motor provided proper safety devices are installed.

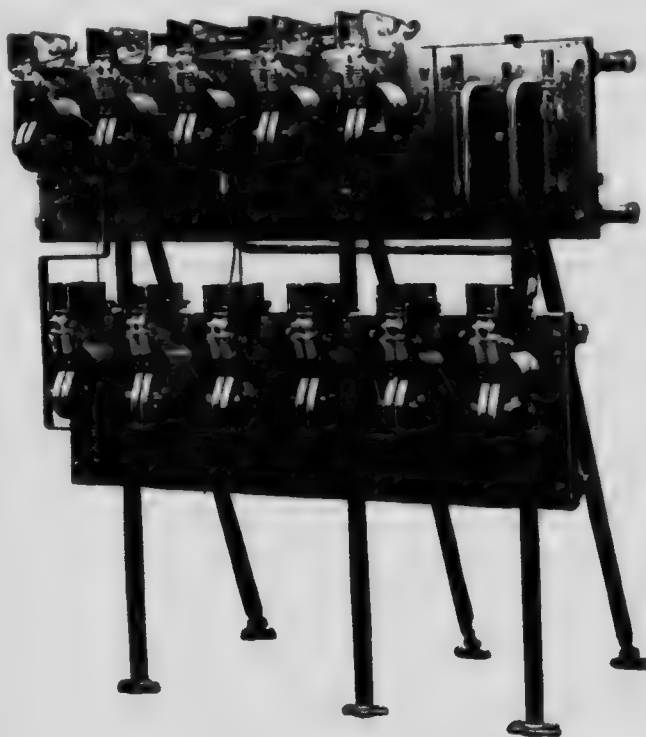


Fig. 679.—B. T.H. Contactor Control Panel for 100 H.P. Motors

Contactor Control. For motors larger than 15 B. H. P. the sliding contacts of the face-plate starter of Fig. 678 are themselves replaced by a series of contactors operated by a master controller.

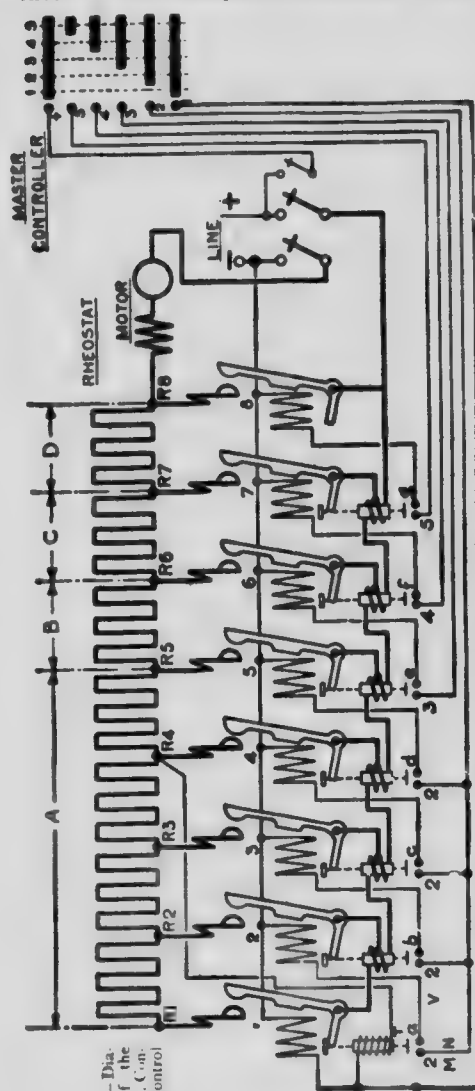


Fig. 680.—Diagram of the B. T. H. Contactor Control Panel

The necessary contactors are mounted on a conveniently arranged panel, and such a panel for the operation of a reversible haulage motor of 300 B. H. P. at 500 volts is shown in Fig. 679. The "line" circuits of the contactors which, as explained above, are "relays" on an engineering scale, are operated by a master controller, which can, of course, be placed in any convenient position at any distance from the panel, but the latter, for obvious reasons, should be placed close to the motor.

A diagram of the connections, contactors, and master controller contacts, but without the reversing circuits, is given in Fig. 680, and one of the contactors is shown separately and on an enlarged scale in Fig. 681. In some details, which are not unimportant, it differs from the contactors shown in Fig. 678; reference will be made to these in due course.

The first operation for starting up is to close the three single-pole switches on the right-hand upper panel of Fig. 679; these make the panel and the master controller alive, but nothing happens until the latter is operated. It will be noticed that the closing of these switches puts the main — direct on to the motor, which

is depicted as a series motor, and also on to a return lead common to the operating solenoids of all the contactors.

On turning the master controller to the first stop the operating solenoid of contactor No. 1 receives current through the fingers + and 1 of the master controller, being bridged through this path right across the mains. The contactor closes its main circuit, and passes a power current to the motor, this current traversing the whole of the resistances R 1 to R 8 which are now connected in series with the motor, and also the small solenoids of contactors 2 to 7. Simultaneously another solenoid T receives a shunt current by a circuit bridged across the + terminal and the point R 4 on the resistance. This extra solenoid, which, it will be noticed, is depicted for all the contactors except No. 8, is the "fool-proof" device designed to counteract too rapid a movement of the controller cylinder. The extra solenoid acts as a "set-up" safety relay. It is placed over the two contacts seen underneath the contactor in Fig. 681, and when its plunger is raised the disc plate which is carried by the plunger floats clear of these contacts. When the plunger drops, this plate short-circuits these contacts. When the contactor is open the plunger is also held in the open position by a mechanical device, but as soon as the contactor is closed this is freed and the plunger is upheld against gravity only by the electro-magnetic action of the solenoid. When the current in the solenoid falls below a predetermined value it drops and short-circuits the contacts referred to. On the first closing of No. 1 contactor, with the motor standing still, there is a big rush of current through the rheostat and the coil T. The plunger of T, with its disc, therefore floats above the contacts; but as the current diminishes with the speeding up of the motor and the production and increase of its back E. M. F. at a certain stage the contacts *a* (Fig. 680) are closed and the operating coil of contactor No. 2 receives current, provided the master controller has been moved to position "2" or beyond, and this contactor closes, cutting out the section R 1, R 2 of the resistance. The current to the motor then momentarily increases, and this series current passes through some of the coils of the safety solenoid of No. 2,



Fig. 681.—A Single Contactor.

holding up its plunger until the motor speeds up sufficiently for the current to fall below the predetermined value at which the relay plunger of No. 2 will be dropped and the contacts *b* short-circuited, passing on current to contactor No. 3. In the same way, contactors Nos. 4, 5, 6, 7, and 8 receive current only when the safety relay device of the preceding contactor allows, and the operation is completed when the plunger of No. 7 drops its disc upon the contacts *g*, and thus causes the pull-on or operating magnet of No. 8 to receive current and to close the main circuit of No. 8, cutting out the last of the rheostatic resistances. Contactor No. 8 is, for obvious reasons, *not* provided with the solenoid and plunger. It should be noted that the load current does not pass through all the coils of the safety solenoid which is to act next; its plunger will therefore drop before the other plungers of the solenoids in circuit.

In Fig. 679 there are three more contactors shown than in the diagram of Fig. 680. These extra contactors are to make the necessary contacts for reversing the motor, the master controller having additional contacts for the reversing circuits. With the information already given here and at page 646 it will be a useful exercise for the student to work out how these contactors are thrown into circuit so as to accomplish the ends aimed at.

Speed Controllers. The apparatus just described has been chiefly that designed for the purposes of starting the motors with added devices to enable them, when once started, to be left running properly protected against certain contingencies which may quite frequently arise.

Now and again, notably in Figs. 660 and 670, the apparatus illustrated has gone farther than these requirements, and has included the apparatus necessary for varying or controlling the speed of the motor by the introduction of resistance into or its removal from the circuit of the shunt field coils. The theory of this method of speed control has been fully discussed in the last section (see pages 648 to 653). For series motors, and also for shunt motors, the starting resistances, which are placed in series with the armature, may be used for the purpose of controlling and varying the speed, though in most of the apparatus described these resistances are so arranged that when the motor is fully started they are either short-circuited or entirely switched out of circuit. Moreover, a method of speed control which uses resistances traversed by heavy currents, is, as has been shown elsewhere, uneconomical. Leaving series motors, however, to the chapter on traction, most of the general types of apparatus described for supplying resistances for starting can be adapted for the supply of resistance for the shunt field circuit of shunt motors, and it will be convenient to refer to these types in much the same order as in the previous pages.

Face-Plate Controllers. - For the speed control of shunt-wound motors, since the control, within the possible limits, is most economically obtained by altering the excitation current in the field magnet circuit, a sliding con-

tact rheostat, which is only required to carry comparatively small currents and which therefore may very conveniently be of the face-plate type, is all that is necessary. In making up panels for motor working, such as are illustrated in Fig. 674, it is therefore quite customary to add such a rheostat to the equipment of the panel, and an example of this has already been given in Fig. 666, in the panel designed by Messrs. Brook, Hirst and Co. This feature of the panel is shown on a larger scale in Fig. 682. Below the starter there will be noticed the fixed contacts of a rheostat and a hand wheel for moving the radial arm, which carries the sliding contact or wiper. This rheostat is placed in series with the field-magnet coils across the mains and, by increasing or diminishing the resistance, the field flux can be weakened or strengthened and the speed increased or diminished.

One obvious precaution should be taken, and that is so to interlock the starter and the speed controller (i.) that the starter can only be operated when no part of the rheostatic resistance is in circuit, and (ii.) that the rheostat hand wheel cannot be moved from the zero position until the starter arm is "full on." Such an interlock is used in the panel referred to, and it is only by an effective device of this kind that the dangerous contingency of putting full voltage on to the armature circuit whilst the field flux is weak can be avoided.

Drum or Cylindric Controllers.—In the example given above of the face-plate type of controller the shunt regulator was a piece of apparatus separate from the starter, and worked with a separate handle or lever. It is one of the advantages of the drum or cylindric type of multiple switch that it is possible to design it so that the starter and the controller are operated by the same handle. An excellent example of this modification is given in Figs. 683 and 684, which illustrate a starter and controller designed by Messrs. A. Keyrolle and Co., Ltd. Fig. 683 is a simple example of the apparatus, consisting of the switching arrangements without the necessary resistances, whilst Fig. 684 shows a complete outfit with all the resistances, circuit breakers and other apparatus contained within the casing. In Fig. 683 the stationary fingers with which the segments on the rotating barrel make contact are seen attached, with



Fig. 682. — A Motor Starting Panel with Interlocked Speed Controller

of course, proper insulation, interposed to a vertical bar which is secured to the two end plates. At the top of the barrel there can just be seen a blow-out coil, which is the only additional apparatus on the controller itself. At the top of the handle there is a press button, by pressing which in an emergency the controller barrel is released and immediately flies to the "off" position.

In both controllers the method of operation is simple, though not identical. In the more complete controller shown in Fig. 684 it consists in first moving the handle to a clearly-marked starting position and waiting till the motor gets well started. The rotation of the handle is then continued, cutting out the starting resistance step by step until the first revolution of the handle is nearly completed. The motor is then fully started, but the rotation may still be continued; but now the shunt regulator only is operated, resistance being thereby introduced into the shunt circuit step by step, and the motor speeded up to any speed within the limits available.

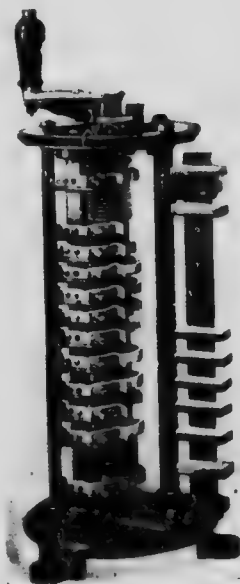


Fig. 684.—The Revolve C. C. Reversible Controller.

In the actual apparatus the segments for the starter are mounted on the middle section of the rotating barrel, and are flanked on either side by the resistances *RR* required for starting and regulating. The contacts for regulating are mounted in a horizontal plane upon the flat slab *s* higher up, and thus in their method of arrangement the plan of a face-plate controller is followed. The no-voltage coil *x* and the overload coil *o* are in the bottom of the case on the right-hand side of the rotating barrel, and the main switch or circuit-breaker *M*, which is tripped by *x*, is also in the bottom of the case on the other side of the barrel. This circuit-breaker can also be tripped by pressing the push-button *P*, and it will be noticed that there is a hole *p* in the cover door to enable this to be done in a case of emergency without opening the controller. There is further a change-over switch *C* just under the top cover.

To explain more clearly the details of the working, Figs. 685 and 686 give a plan and side elevation of the cast-iron cover-plate of the controller, showing the clear instructions which are lettered thereon.

The indicator of the hand wheel being in the position marked "off," the first operation consists in moving the hand wheel quickly in a clockwise direction to the position marked "wait here until motor starts."

This operation throws the connections into the position of the first "live" stop of an ordinary cylindric or face-plate starter. The resistance, however, for reasons to be given later (see page 682), is such that, as it becomes heated with the current, its resistance diminishes; this, however, takes time, and meanwhile the motor is speeding up. When the motor is running steadily, though slowly, the rotation of the hand wheel is continued.

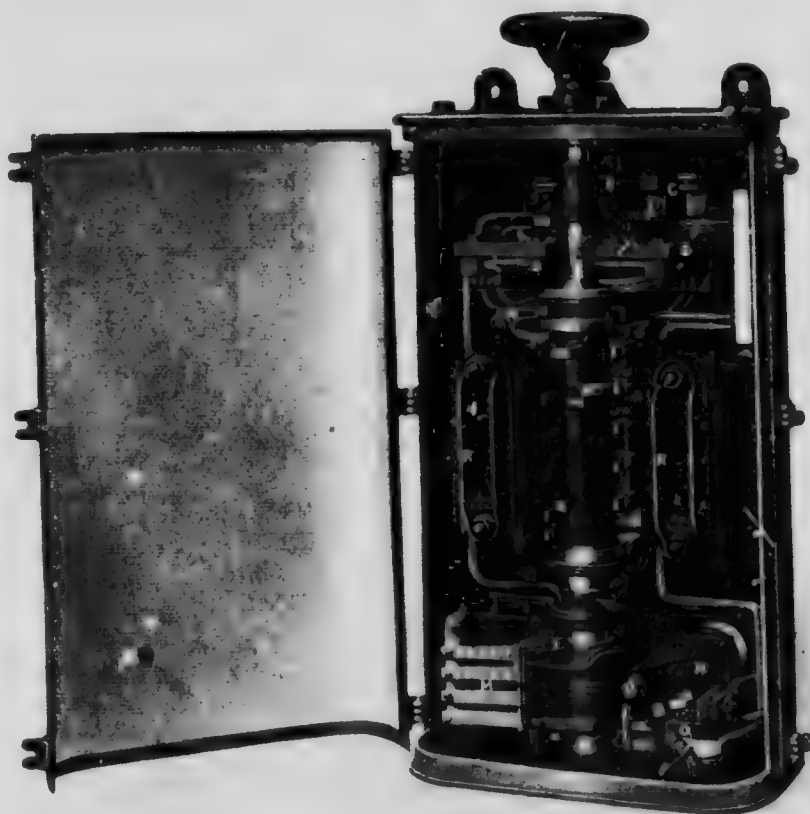


Fig. 684.—The Reyrolle Double-Revolution Drum-Type Starter and Controller.

and successive resistances are cut out until the position "full on" is reached, but it will be noticed that owing to the initial change of resistance on the first stop, that stop has acted as a multiple stop. At the position marked "full on" the motor will run according to the conditions of load at the speed corresponding to the full excitation of the shunt field. If it be required to speed-up further, the rotation of the hand wheel can be continued, but it will be noticed that there is a projecting stop (Fig. 686) at the "full on" position, and if the rotation be continued, the

"starter" part of the barrel remains stationary, and at the commencement of the continued motion the change-over switch *c* (Fig. 684) is thrown over. This permanently short-circuits the starting resistance (already cut out) and its leads, and places the regulating rheostat *s* in series in the shunt circuit with the field coils; at the same time the contact arm *s* commences to move with the wheel. The result is that resistance is introduced into the field-magnet circuit step by step, there being seventeen steps in all.

If, during the rotation of the hand wheel, the circuit breaker is tripped through the direct action of *x*, *o* or *p*, the hand wheel will have to be

allowed to go back to the "off" position before a fresh start can be made. Then the first motion of the hand wheel from the "off" position closes the circuit-breaker.

The British Thomson-Houston cylindric controller has already been illustrated in Fig. 670. The contact fingers for the shunt regulating resistances can be seen

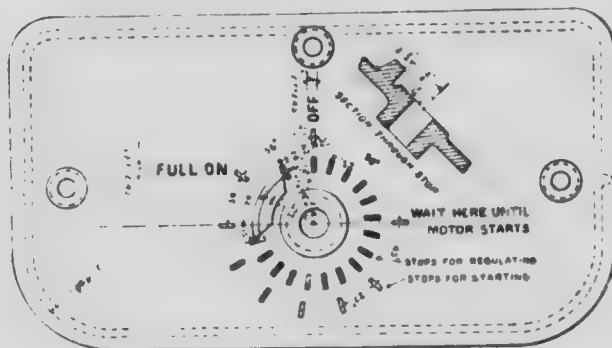


Fig. 685.—Plan.

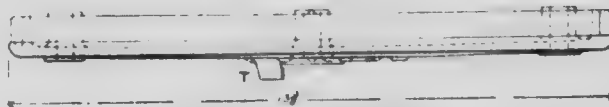


Fig. 686.—Side Elevation.
Cover-Plate of the Reyrolle Starter and Controller

on the right and left to the number of twelve on each side, at the upper part of the enclosure. The moving segments, however, are different from those hitherto illustrated, inasmuch as they are all comprised on two portions of a cylindric surface, one of which, *s*, shows white in front and the other can be seen behind. The sloping edges of these segments are stepped in a kind of *echelon* formation, so that, for instance, if the handle be rotated clockwise, the successive steps of *s* will reach the fingers on the right successively, commencing with the top finger, and proceeding regularly downwards at very short angular intervals in the movement of the handle. The back segment is similarly making contact with the right-hand fingers, but so that its contacts are intermediate between those of *s*. In this way, with the contacts available, no fewer than twenty-three running positions are obtained, and as there are four others on the starting contacts, altogether this starter and controller gives twenty-seven running positions at different speeds. The segments referred to above are so placed

on the barrel that no additional resistance is introduced into the field circuit until the "full-on" position has been reached with the starter section of the controller.

Resistances for Starters and Controllers.—In all the starting and controlling devices described in this section, the necessary control is obtained by using a resistance which is required to absorb energy. The particular type of resistance used is obviously of great importance, and in most of the starters and controllers described metallic resistance, of one form or another are employed. On pages 183 to 185 some typical forms of resistance used for the field control of C. C. dynamos have been described, and these are, of course, available for motor control, provided they are designed to carry the currents and absorb, without detriment, the energy to be handled. In several of the illustrations just given other forms of metallic resistance are clearly discernible and should be carefully examined.

The metallic resistances described at page 182 *et seq.* consist of open spirals of wire, of wires buried in cement or an insulating compound and mounted on plates or tubes and, for the heaviest work, of metallic grids suitably mounted. Grids of other types have also been devised. For heavy work these become expensive in material, to reduce the cost of which they are sometimes worked at a dangerously high temperature. Often soldered joints are used, which may lead to interruptions when the temperature rises; short circuits and fusions may also occur.

To obviate some of these difficulties Messrs. Ferranti, Ltd., have developed for motor starters a pattern of resistance in which the resistance material consists of compressed powdered graphite. This has a specific resistance (see Table IV., page 752, Vol. I.) of the order of 1,000 times that of the usual metals and metallic alloys, and, for the quantity necessary to build up the required resistances, is comparatively inexpensive. It is also unfusible and unbreakable, and has a high thermal capacity, or, in other words, requires a large quantity of heat to raise its temperature one degree.

In the Ferranti resistance the material is contained in a rectangular ribbed trough (Fig. 688) made of iron heavily enamelled. This is lined with flexible, non-combustible material and filled with the powdered graphite. Contact plates to form electrodes of the shape shown in Fig. 687 are imbedded transversely in the trough at suitable distances apart, the flexible sides of the trough are folded over and cemented to exclude the air, pressure blocks are inserted, and the whole screwed up whilst under great pressure. The ends of the plate electrodes project and have attached to them, without solder, the leading wires seen in Fig. 688, which depicts the resistance unit for a 10 H. P. starter. These wires are then brought to the contacts on the face plate of an ordinary type of starter, the resistance unit being mounted behind the face plate.

The resistance used in the Revrolle starter described at page 677

(Fig. 684) is designed upon similar lines, the resistance material being powdered graphite with metal-plate electrodes at suitable intervals. It will be remembered that on the first stop of this starter advantage is taken

of the negative temperature coefficient of carbon, the instruction being to keep the starter on this stop for quite a time, with the intention of allowing the carbon resistance to become sufficiently heated for the value of the resistance to be appreciably reduced. The effect is that this stop becomes in reality a multiple stop, the resistance in circuit, whilst the operator is using it, being gradually and continuously reduced by taking advantage of the physical properties of the resistance material.

It will be gathered from the foregoing that the general design for the resistances necessary for starters and controllers consists in providing the maximum resistance required for the circuit to be dealt with and then, by means of tappings, brought to conveniently placed and arranged contacts, to introduce into, or remove from, the circuit such portions of the resistance in such steps as may be found necessary. The great practical defect of the method is that the resistance is introduced and

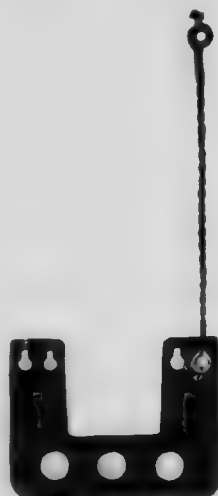


Fig. 687. — Electrode of Ferranti Non-Metallic Resistance.

removed step by step, and not gradually and continuously. To minimise this defect the number of tappings must be increased, but this, especially if the tappings become very numerous, adds considerably to the cost of the apparatus and is, at the best, only a palliative, and not a real solution of the difficulty.

A gradual change of resistance within the limits required is aimed at in the compression type of resistance made by Messrs. Ferranti, Ltd., one form of which has been described in connection with the compression-type starter in Fig. 667. Another form, designed to deal with much larger quantities of energy, is shown in Fig. 689. The graphite discs previously described (see page 663) are in this pattern, mounted on columns or rods, from which they are, of course, insulated, and these rods in their turn are rigidly fixed between two substantial end plates A and B, between which other stays and guides are used. A movable plate C can slide along the guide and

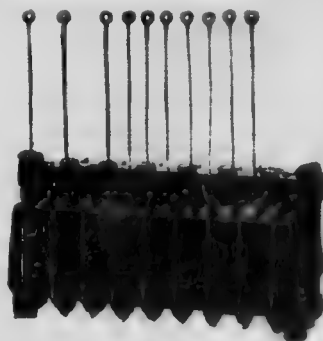


Fig. 689. — Ferranti Resistance Unit for a 10 H.P. Starter.

stays, from which it is insulated by porcelain tubing. The plate forms one of the electrodes of the system, the other electrode being a similar fixed plate close to, but insulated from, the end plate A. The plate C can be moved backwards and forwards by the hand wheel W, on the shaft of which there is a screw thread working in nuts in the end plate B. By forcing the plate C to the left the discs which form the conductive connection between the two electrodes will be compressed and their resistance reduced gradually and continuously without any sudden change.

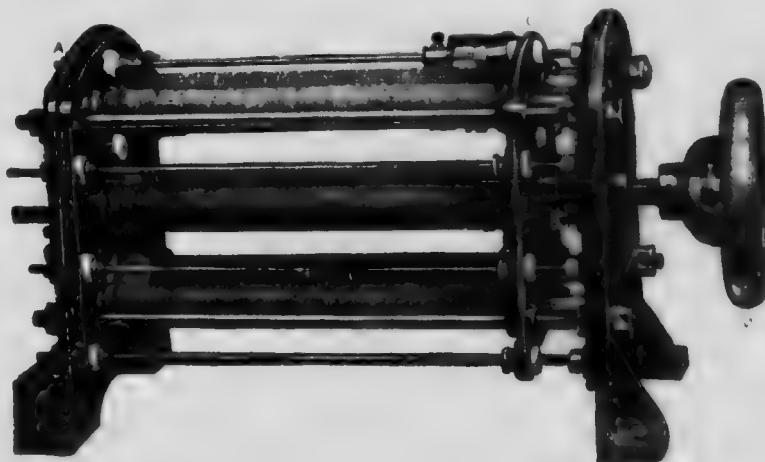


FIG. 680. The Ferro-ti Compression Type of Variable Resistance.

By choosing an appropriate thread for the spindle of W, or by turning the wheel at a different speed, the rate of compression, and with it the rate of change of resistance, can be varied. The actual range of the change of resistance obtained in practice is from 80 to 1.

In these resistances, since there are no contact studs for the subdivision of the resistance, sparking at the contacts is abolished; there can also be no interruptions from burnt-out coils, and it is claimed that short circuits are impossible. On the other hand the re-introduction of the resistance into the circuit is not quite so definite a matter, owing to adhesion between the discs.

Rating of Starters.—The rating of starters, that is, the size of motor which a particular starter is capable of dealing with, is a question in which, like the rating of the motors themselves, all the conditions of the problem must be taken into account. Looked at from the point of view of rating, the starter is, when fulfilling its primary function, an absorber of energy, which it converts into waste heat, which must be got rid of with reasonable rapidity. Since the amount of energy to be absorbed depends on the

currents which the starter resistances carry, it is clear that the B. H. P. of the motor to be served is not by itself a sufficient guide; the voltage also must be specified.

As bearing upon the same group of conditions, it is important to specify whether the motor is to be started on full load or on light load, for this will obviously affect the currents to be used and the time taken.

A still further point is the length of time to be taken by the starter in completing a single "start." Here again, if the start can be made rapidly the resistances will not be called upon to absorb as much energy as they would have to take charge of if the "start" were spread over a longer period.

Another very important point is the frequency with which the starter

will be likely to be used. Obviously a starter which is only used at long intervals and has time to cool down between successive operations, may be rated higher, other things being equal, than a starter which is used at intervals so



Fig. 660.—Armature of a Motor showing the Effects of Excessive Speed.

short that it is still warm from previous use when it is again called upon for service.

In specifying the rating of a starter, therefore, all these points should be referred to. For instance, the rating of the Westinghouse multiple switch starter (Fig. 672), described above, is given officially as follows:—(i.) As regards time, it can be used at fifteen-minute intervals for a period of 1 minute up to 250 B. H. P., $1\frac{1}{2}$ minutes from 250 to 500 B. H. P., and 2 minutes from 500 to 1,000 B. H. P., and (ii.) as regards load against full-load torque on first step up to 100 B. H. P., 100 volts or 150 B. H. P., 200 to 600 volts; $\frac{2}{3}$ -load torque on first step and full-load torque on second step for 100 to 300 B. H. P., 100 volts and 150 to 300 B. H. P., 200 to 600 volts; for larger motors, 60 per cent. full-load torque on first step and full-load torque on second step. The student should care-

fully think out what is implied in the various parts of this specification. It will be noticed that the maximum excess temperature of the rheostat resistances is not stated.

Breakdowns.—This section and chapter cannot perhaps conclude better than with illustrations of what may happen when precautions break down and an electric motor runs away. In Fig. 690 and 691 are shown, reproduced from photographs, armatures of motors which have run away through the failure of one or more of the protective devices considered in this section. If these fail to act, then one has to remember that the amount of energy connected up to the circuits of the

motor and available to do mischief is for the size of the motor very great indeed, and that the motor may be driven up to a speed many times more than that for which it is designed, a speed at which the mechanical appliances for counteracting the effects of centrifugal force may utterly break down. This is what has happened in both the cases illustrated. In Fig. 690 the speed has been so great that the binding wires on the end connectors have burst, and these connectors have fanned out as shown. It is significant

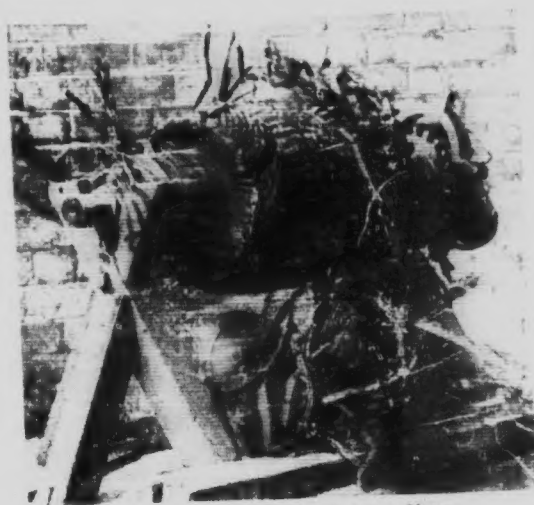


Fig. 691.—Armature of another Runaway Motor.

of the great mechanical forces called into play that the laminated teeth of the armature core at the pulley end have been raked considerably out of straight alignment with their fellows at the commutator end. In Fig. 691 the end connectors, or at least those at the commutator end, have fairly well held together, though they were raked out of their original positions. The conductors and their insulating materials on the armature slots, however, have burst outwards *en masse*, with the results depicted. The two figures are, taken together, an "awful example" of the necessity for the greatest care in the design, construction, and installation of proper safety devices.

The opposite case to the above is where the motor armature is held or jammed without the safety appliances acting, leaving full voltage on the motor. It is almost inconceivable that this should happen,

but if it did, the rise of temperature of the copper circuits would be very rapid indeed, and in a short time and for as long as the copper held together the motor might become an example of a highly inefficient electric furnace for fusing copper.

END OF SECTION I., VOLUME II.

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